

LA-UR-21-22252

Approved for public release; distribution is unlimited.

Title: LA-R43S6-L1 Postshot Report

Author(s): Goforth, James H.; Armstrong, Christopher Lee; Baca, Eva V.; Dickson, Peter; Farnsworth, Conrad Jackson; Foley, Timothy J.; Gianakon, Thomas Arthur; Gielata, Janina Anna; Glover, Brian B; Gunderson, Jake Alfred; Meyer, Ross Keith; Herrera, Dennis H.; Oona, Henn; Rae, Philip John; Rousculp, Christopher L.; Watt, Robert Gregory; Haroz, Erik H.

Intended for: Report

Issued: 2021-03-08

Disclaimer:

Los Alamos National Laboratory, an affirmative action/equal opportunity employer, is operated by Triad National Security, LLC for the National Nuclear Security Administration of U.S. Department of Energy under contract 89233218CNA000001. By approving this article, the publisher recognizes that the U.S. Government retains nonexclusive, royalty-free license to publish or reproduce the published form of this contribution, or to allow others to do so, for U.S. Government purposes. Los Alamos National Laboratory requests that the publisher identify this article as work performed under the auspices of the U.S. Department of Energy. Los Alamos National Laboratory strongly supports academic freedom and a researcher's right to publish; as an institution, however, the Laboratory does not endorse the viewpoint of a publication or guarantee its technical correctness.

LA-R43S6-L1

Postshot Report

J. H. Goforth, C. L. Armstrong, E. V. Baca, P. Dickson,
C. J. Farnsworth, T. J. Foley, T. A. Gianakon, J. A.
Gielata, B. Glover, J. A. Gunderson, R. K. Meyer, D. H.
Herrera, H. Oona, P. Rae, C. Rousculp, R. G. Watt

Los Alamos National Laboratory

Erik Haroz

Mission Support & Test Services- Los Alamos
Operations



This report is dedicated to the memory of Brian Glover who played a major role in the execution of this test, and whose friendship, knowledge, and talents will be long remembered and sorely missed by us all.

OUTLINE

- Abstract
- Introduction
- Experimental design
 - Schematic
 - Seed source
 - Ranchero R43S6 FCG
 - Liner
 - Slapper Detonator x-unit
- Results
 - Diagnostics layout
 - Seed source
 - FCG
 - Liner
- Conclusions

Abstract

The Ranchero LA-R43S6-L1 test (formerly referred to as LA-43S-L1. The R specifically designates it is a Ranchero device and the 6 indicates a 6" high explosive charge diameter in anticipation of using larger diameters in the future.) was conducted on 3/8/17 with good success. The experiment was the first test of a "Swooped" Ranchero flux compression generator (FCG), and the load for the test was an aluminum imploding liner. In addition to the swoop, the stator was anodized to provide an insulating layer instead of one or more layers of polyethylene as had been the case for all earlier Ranchero tests. Using the Firing point TA-39-88 capacitor bank, 3.5 MA was delivered to the FCG for the initial magnetic field, and 36.4 MA were delivered to the load having an initial inductance of 2.5 nH. Implosion speeds over 1.1 cm/us were recorded, which exceeds previous LANL solid liner experimental results. The test was diagnosed with 18 PDV channels, 12 of which recorded liner implosion data, and the other 6 of which tracked the FCG armature during flux compression. These armature expansion data recorded during flux compression are the first of their kind, and it was previously unknown, due to unknown effects of the SF_6 in the flux compression volume, whether or not the expansion could be recorded using the PDV technique. Post shot 2D MHD calculations employed a complete external circuit model, and an improved flux diffusion model not available prior to the test. Results from these simulations show very good agreement with the experimental result. Four PDV channels recorded the liner implosion viewed radially outward from the center of the liner. All four of these probes recorded implosion velocities greater than 1 cm/ μs , with the cylindrical center displaced by ~ 2 mm from actual center. Four PDV channels looked at $+10^\circ$ angles from the CMU wall, and four looked at -10° angles. A glide plane interaction is shown moving toward the center of the liner in MHD calculations, and PDV probes provide confirmation.

The high explosive (HE) in the LA-R43S6-L1 test was PBX 9501 which had to be glued together in many pieces, and the test was preceded by a camera test to verify that the PBX 9501 could be assembled with acceptable tolerance in glue joints to prevent severing the armature during expansion. The camera test verified an acceptable armature performance, and results are given in complete detail in a post shot report LA-UR-19-20124 [1], and summarized here.

This report provides complete detail of the considerable body of data obtained on the test and in the post shot calculations. It is prepared in Power Point for ease of preparation and future review. Shot documentation available in the LANL on-line library are included as references, and non-referencable documents will be cited and stored in an LA-R43S6-L1 post shot folder stored on an M-6 shared drive. Fabrication drawings are also maintained in an M-6 shared drive and paper files are available from M-6 personnel. This report will be maintained as a PowerPoint document on the shared drive, as well, since included movies will play and graphs from Excel files retain information in the PowerPoint versions. PDF versions are required for clearance and are not too large to send by e-mail.

Introduction – page 1

LA-R43S6-L1 tested a new model Ranchero flux compression generator (FCG) which drove a solid density imploding liner z-pinch. It was deemed appropriate to combine the initial FCG and liner tests, because there is considerable confidence that as long as a Ranchero armature performs as expected, the FCG will also. The test was preceded by small scale tests to demonstrate that sufficiently thin glue joints would not rupture the armature during expansion, and then a full scale camera test to demonstrate that the armature behaved as in hydrodynamic calculations [1].

Swooped FCG

Ranchero FCGs were first tested in October of 1995 and solid liner implosion tests were conducted in 1999 using a fuse opening switch (FOS) to shorten the load pulse duration to $\sim 5\mu\text{s}$. Those tests were aimed at demonstrating that the proposed load design for Atlas would function. With 8.4 nH in the load circuit beyond the FOS, a peak current of 15 MA was generated using a 43 cm Ranchero module, and 18 MA using a 1.37 m module. In both cases, the point 88 capacitor bank was used for initial current. Implosion velocities of 6.3 and 6.8 km/sec, respectively, were achieved. In 2008 and 2009 another series of tests was performed to demonstrate proof of principle for a liner impact concept funded out of the LDRD office. These tests used explosively formed fuse (EFF) opening switches to limit the duration of the load current pulse to the FCG function time of $\sim 27\mu\text{s}$. The initial load design had an inductance of 13 nH, and using a static inductance load of that value, a 1.37 m Ranchero module with initial flux from the point 88 capacitor bank, generated ~ 31 MA. To double the data rate, the final load was configured with two liners in series, and the initial load inductance increased to 19 nH. The extra inductance limited the peak current to 18 MA, but one of the liners achieved an implosion velocity of 9 km/sec and the other demonstrated the desired liner impact physics. Finally in 2011, a test was conducted to demonstrate the high current performance of the standard Ranchero 43 cm module design. The test was conducted with a minimum inductance (~ 0.5 nH) load, consisting of only a diagnostics groove, and with an initial current of 3.75 MA from the point 88 capacitor bank, 76.2 MA was generated. At the time that the “Ranchero Status Report 2012” [2] was published, the claim was intact that standard Ranchero modules with an output circumference of 96 cm could be operated at currents up to 96 MA, following the rule of thumb that FCGs should be limited to an operating current of 1 MA/cm of conductor width. Even though the 76 MA test compared well with pre-shot calculations, detailed post shot analysis revealed that a design flaw was initiating an aneurism near the (continued next page)

Introduction – page 2

output glide plane that would ultimately limit the maximum output current of the FCG as higher currents were approached. The design flaw could be eliminated, but further analysis showed that such an aneurism would occur as current increased, even without it. The Ranchero “S” design eliminates the output glide plane, and thus, the region in which the aneurism occurs. In addition, the “S” armature is supported near the output by increased HE pressure, and does not rely entirely on armature kinetic energy to compress flux. However, the output radius of the “S” design is reduced from that of the standard module, and the peak current that can be expected from the initial design is still limited to 75 - 80 MA for loads of substantial inductance, as is discussed in “Predictions for the drive capabilities of the RancheroS Flux Compression Generator into various load inductances using the Eulerian AMR Code Roxane,” LA-UR-16-23924 [3] and “The search for a 100 MA RancheroS magnetic flux compression generator,” LA-UR-16-26685 [4]. Along with the need to eliminate aneurisms at high current, there was also a notion that “sculpting” the shape of the Ranchero output could be used to tailor the drive to some desired output wave form. However, it was quickly realized that the highest performance that could be expected was given by a simultaneous closure along the entire FCG length. Experimental results have indicated that losses for FCGs with simultaneous closure are larger than for designs with a slight taper along the stator as the armature closes the gap [2]. Thus, the initial Ranchero S has a zippering feature, and the two major benefits of the design are that it adds ~30 nH to the initial inductance of a Ranchero with any length detonator, and that it maintains slightly higher HE pressure on the armature near the output. Throughout the history of Ranchero development and applications, polyethylene was used to provide an insulating layer along the stator, whether zippered or not. The 2012 Ranchero Status report [2] presents a detailed accounting of that parameter. For the swapped Ranchero design we elected to provide that insulation via an anodized layer on the stator. An additional design change was to employ PBX 9501 HE for this generator to provide higher performance even though at higher cost. That decision led to a concern about the effect of the sharper PBX 9501 pressure profile on the aluminum armature. This was explored in an experiment, and reported in “Ranchero Armature Test LA-19.4-CT-3: PBX-9501 Explosive with no smoothing layer, Firing point 88, 9/16/13” LA-UR-14-28810 [5]. There were also concerns about the effect of glue joints on armature performance and further small scale tests were conducted. These were summarized in “LA-43-S-CT Post Shot” [1] and given in detail in “Small scale tests ’15 Post Shot draft,” (Appendix I in LA-43S-L1 folder which is available on an M-6 shared drive). There are two significant conclusions from the small scale glue joint tests. The first is that glue joints thinner than 0.002” are adequate to prevent rupturing the armature. The second is that detonation wave interactions from adjacent detonation points must not travel along a glue joint. Finally, a camera test of a complete 43-S armature assembly was conducted to verify that it would function properly. PDV probes were used to characterize the armature motion on the camera test, and on the test we report here, LA-R43S6-L1, PDV probes provided the first-ever look at expansion of such an armature under magnetic loading. A comparison of velocities with and without a magnetic field is provided by these two tests, and a discussion follows about energy extracted from armature kinetic energy as it does work on magnetic field.

Introduction – page 3

Imploding liner load

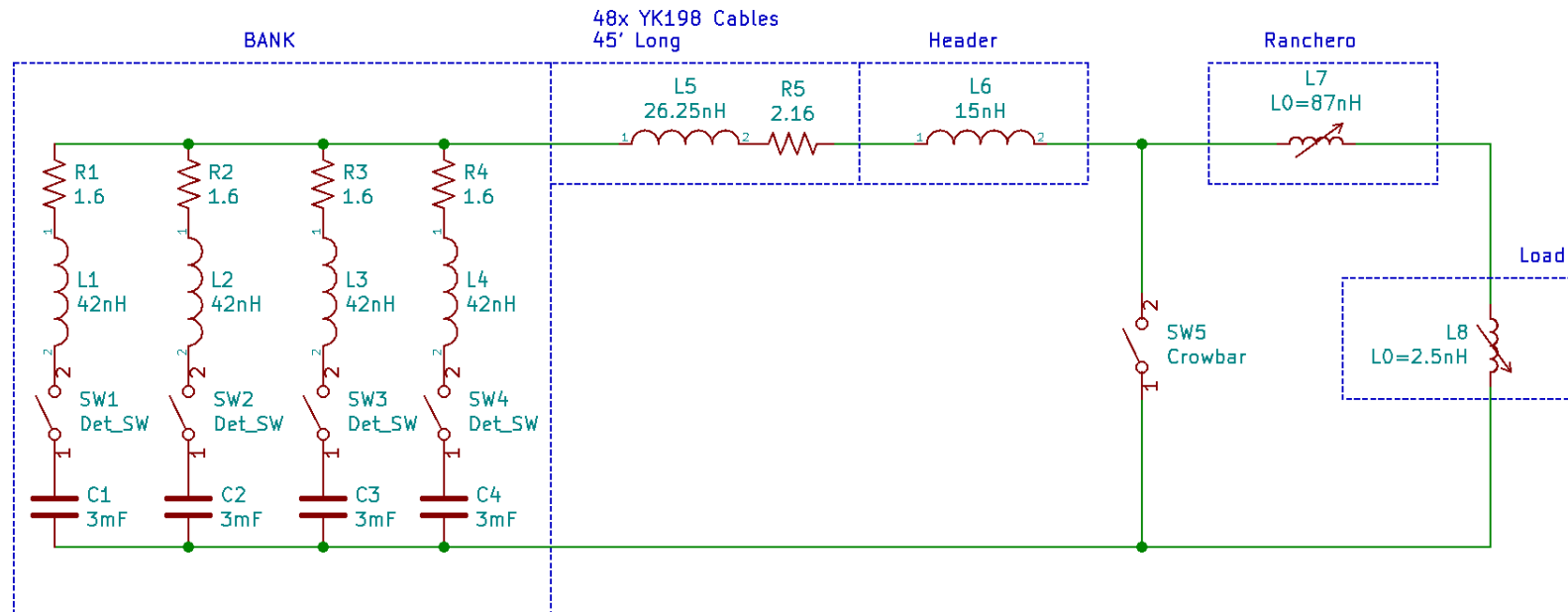
Solid density imploding liners are used to generate high energy densities upon impact with a physics load. The highest implosion velocity achieved on Los Alamos experiments prior to this test was 9 mm/ μ s, and it was a goal of this experiment to achieve speeds of over 10 mm/ μ s. A liner was chosen that was assured to remain solid on the inner surface, but could achieve speeds of up to 2 cm/ μ s. The load consisted of a 7.85 cm outer radius, 3.5 mm thick Aluminum Liner with an initial mass of 182 g. The Aluminum was “Alcon” (near Al 1100 grade) from a lot purchased in the late 90’s and used for essentially all tests of this type conducted by LANL in the intervening period. The gap between glide planes was initially 4 cm and glide planes were curved following the “Atchison philosophy [6],” resulting in a 2 cm separation at the CMU. A 12 probe PDV array measured the implosion perpendicular to the center of the liner, and at + and – 10° angles from the center. Initially, the liner had a mass of 182 g, and at final convergence ~ 50 % of that mass remained.

Experimental design

- Schematic
- Seed source
- Ranchero R43S6 FCG
- Liner
- Slapper Detonator x-unit

LA-R43S6-L1 Schematic

- All branch resistances and inductances are as-fired
- Voltages on the shot were:
 - A –18.75 kV
 - B - 18.62 kV
 - C – 18.09 kV
 - D – 18.17 kV

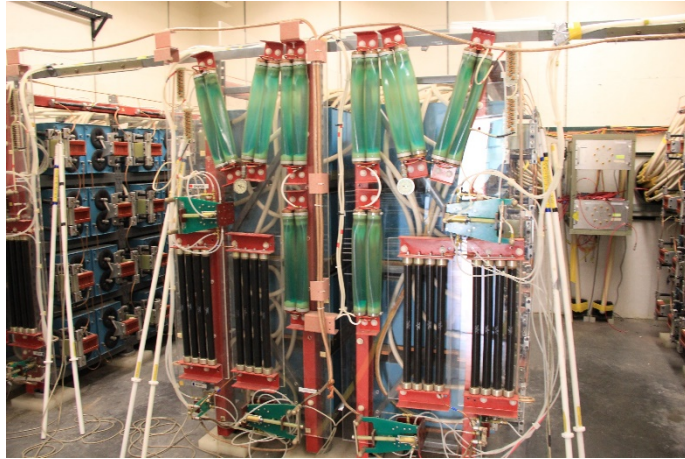


Seed Source

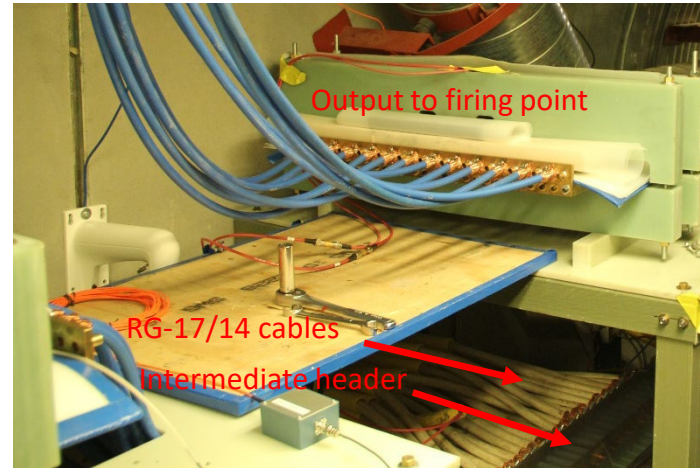
The firing point 88 capacitor bank

Seed Source

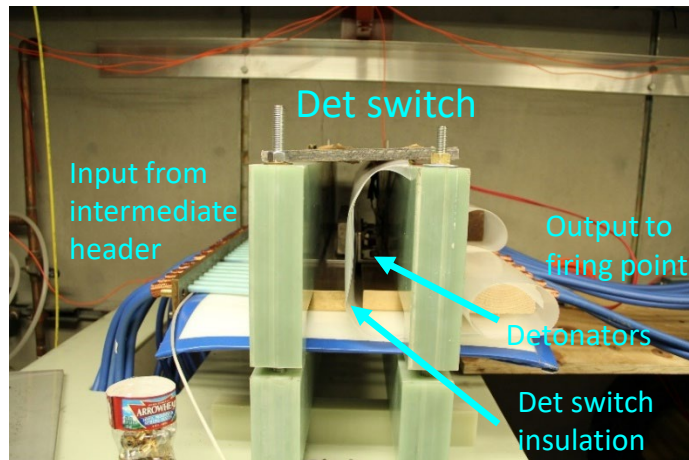
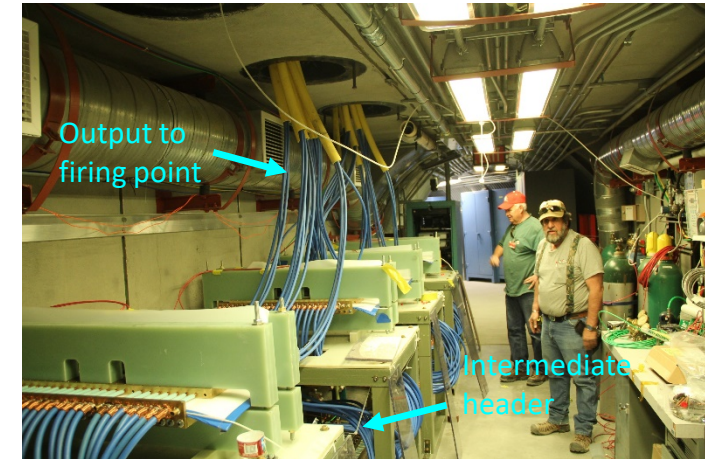
The point 88 capacitor bank consists of four 3 mF modules that can be charged to 19.5 kV. Semi-permanent RG-17/14 cables connect each module to intermediate headers in the tunnel. In a new cable configuration, used for the first time on this shot, 24 cables 6' long connected the four intermediate headers to the four det switches inside the tunnel and 48 cables 45 ft. long connected the det switches to the Ranchero input header.



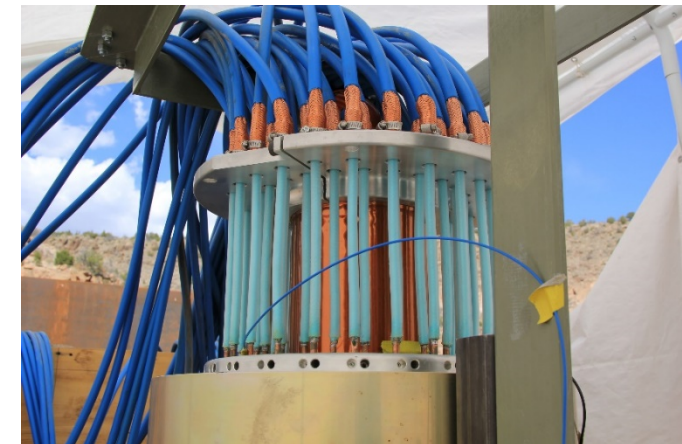
Seed bank – 4 modules of 3 mF at 19.5 kV max



Detonator switches (S1-S4 in schematic) are in the tunnel and seed bank cables connect the det switches to the firing pad.



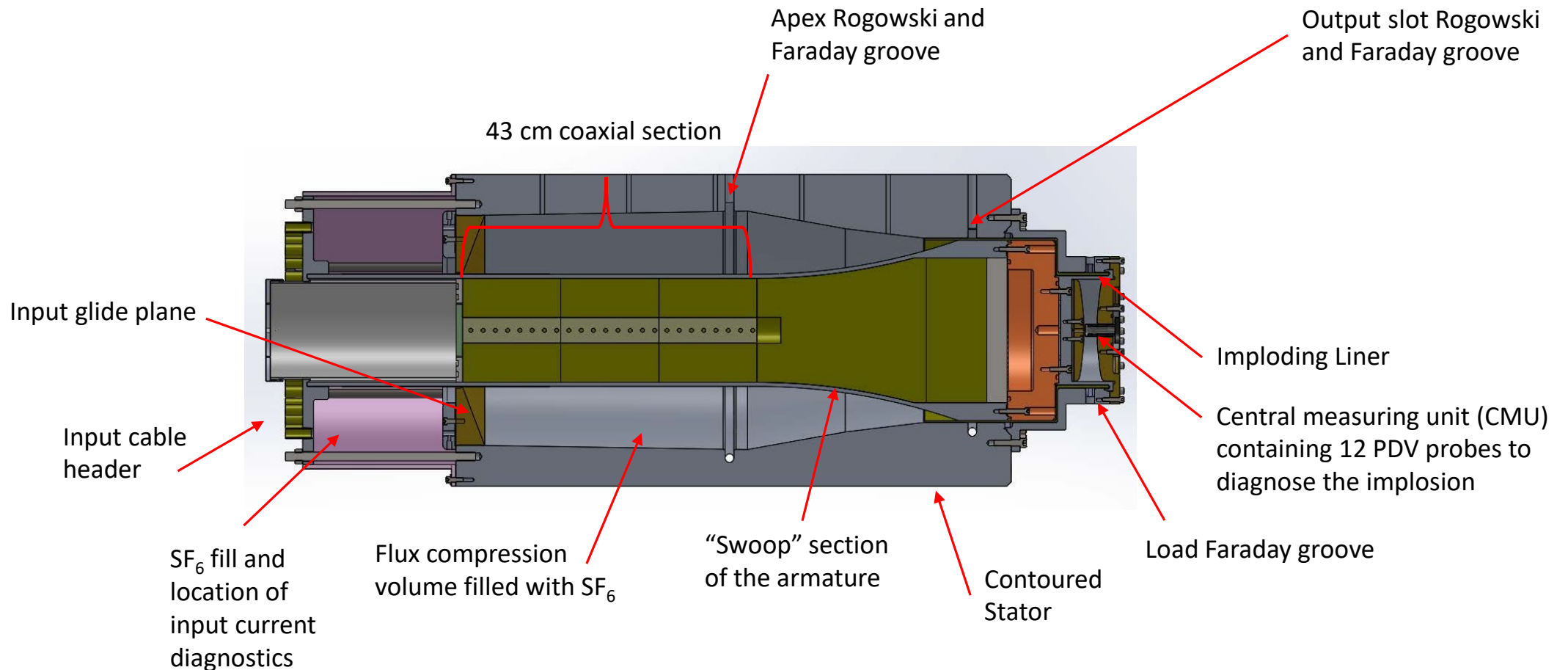
Forty eight 45' cables pass through the blast shield and are routed over the plywood/sand boxes that protect the blast shield area.



48 cable, 15 nH input header; before SF₆ confinement is installed.

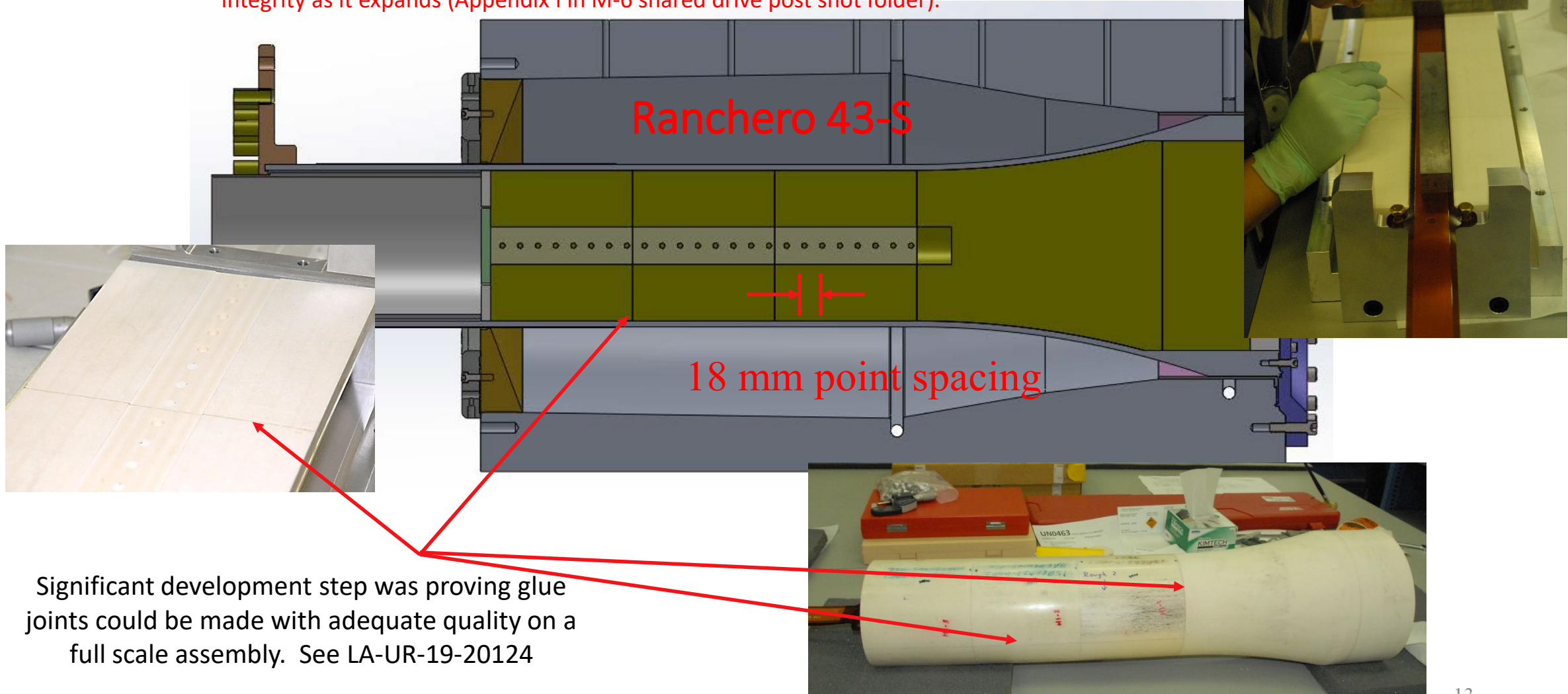
Ranchero R43S6 Flux Compression Generator

Swooped Ranchero generator R43S6 has a 43 cm long coaxial section and a “Swooped” output end as shown.

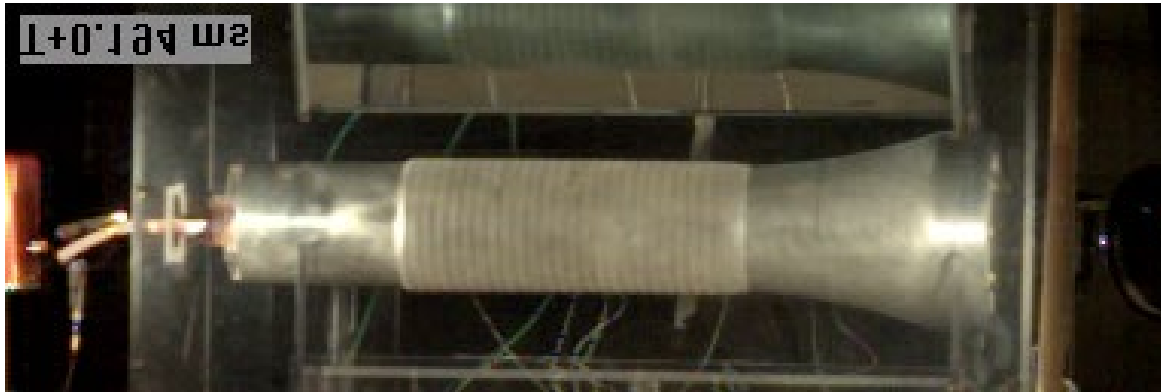


Back-to-back 24 point slapper detonator cables fire 1.65 g/cc ~12,000 cm²/g PETN pellets inserted into both PBX 9501 half cylinders

Note that the glue joints between segments are not centered between pellets. They are offset by 3 mm to assure that the shock wave interactions between pellets do not develop along the glue joint, which has been shown to impact armature integrity as it expands (Appendix I in M-6 shared drive post shot folder).



Simultaneous detonation of the coaxial section and subsequent detonation along the swoop section are key to Ranchero-S performance

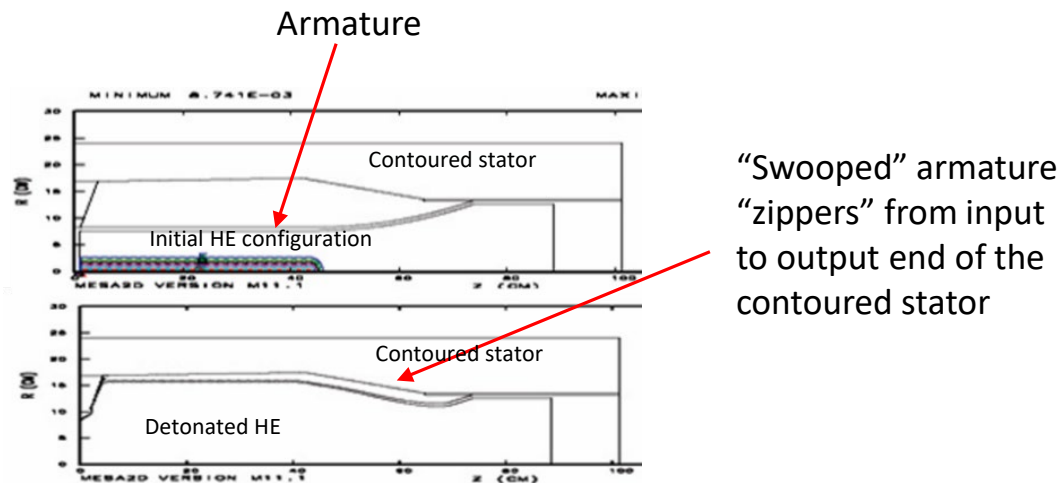


Armature expansion observed during the camera test at a time shortly after breakout of the coaxial detonator section.



Armature expansion observed during the camera test 16 μ s after frame above.

$L(t)$ for the R43S6 Ranchero is given in [3], "Predictions for the drive capabilities of the RancheroS Flux Compression Generator into various load inductances using the Eulerian AMR Code Roxane" LA-UR-16-23924



These figures come from the original MESA 2-D hydrodynamic calculations which determined the armature and stator profiles used in this test.

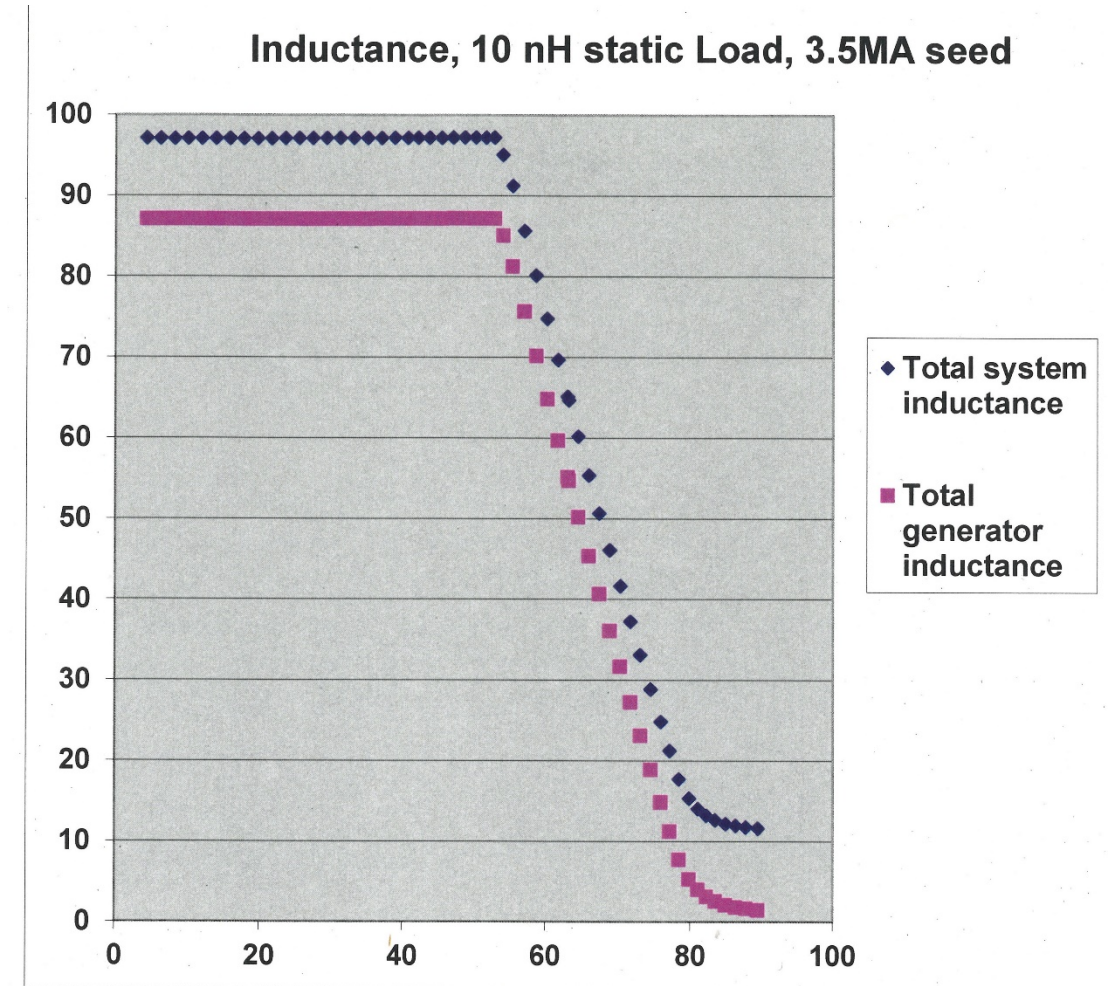


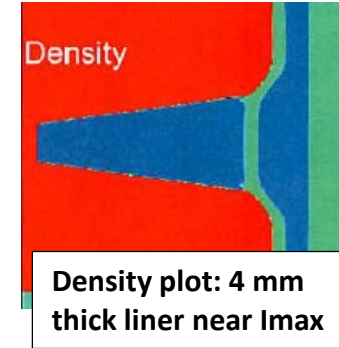
Figure 7. Total system inductance (load + FCG), blue, and FCG SF6 cavity inductance, magenta, from a 10nH load, 3.5MA seed current simulation, in which minimal load or generator distortion due to excessive magnetic pressure occurs.

Liner

Initial liner parameters were surveyed using one and two-D MHD calculations and given in: “**LA43S liner implosions, Roxane results: for discussion and Goforth’s IEEE2015 talk**” (see M-6 shared drive folder Appendix II)

Load survey for LAR43S6 liners using Roxane (~ 2.7nH initial load inductance, 8° straight GP with 0.5” fillet, 250um res.)

Thickness	I _{max}	Condition at 1 cm IR	Velocity at 1 cm IR	Raven 1D velocity at 1cm
1mm	42MA	NA, Disrupted	NA	6.9 mm/us
2mm	39MA	Solid except at GP	13 mm/us	11.23 mm/us
4mm	44MA	Solid except at GP	11.47 mm/us	11.63 mm/us
5mm	44MA	Solid except at GP	10.41 mm/us	11.28 mm/us
6mm	47MA	Solid except at GP	~ 8.8 mm/us	10.91 mm/us

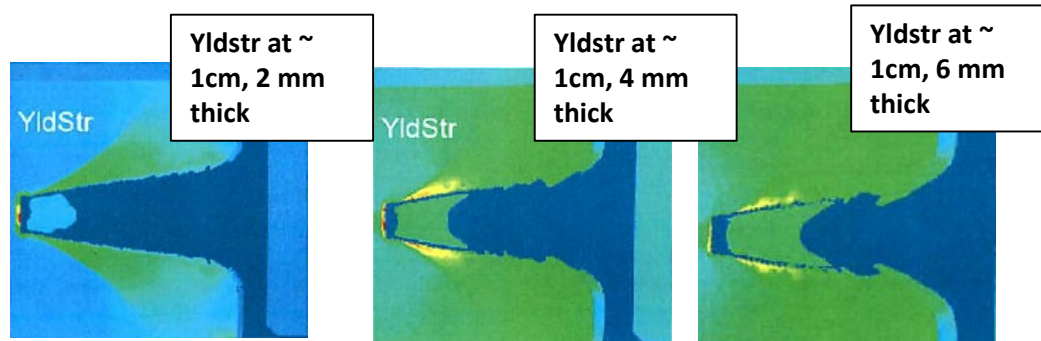


• Final design criteria

- Try to exceed 1 cm/μs implosion velocity
- Maintain solid inner surface

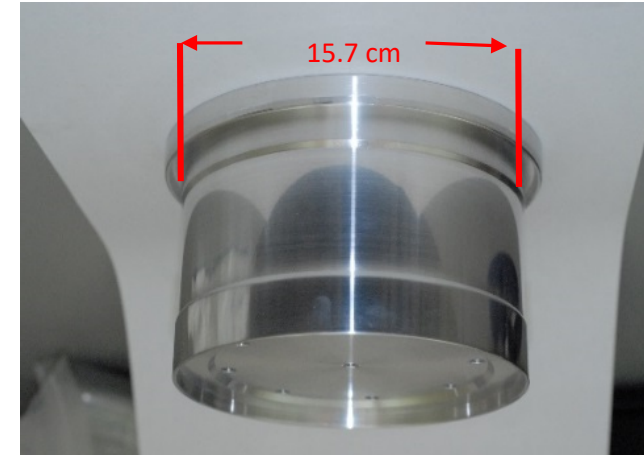
• Final choice

- Liner IR = 7.5 cm; OR = 7.85 cm
- Liner height = 4 cm initial; 2 cm final
- Liner material – ALCON (near Al 1100 grade)

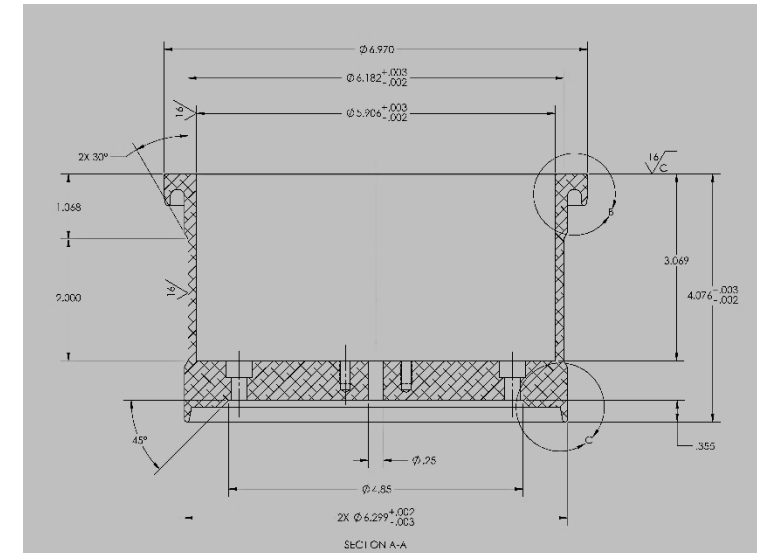
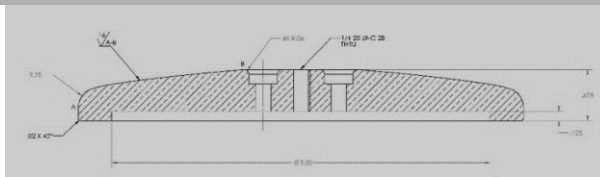
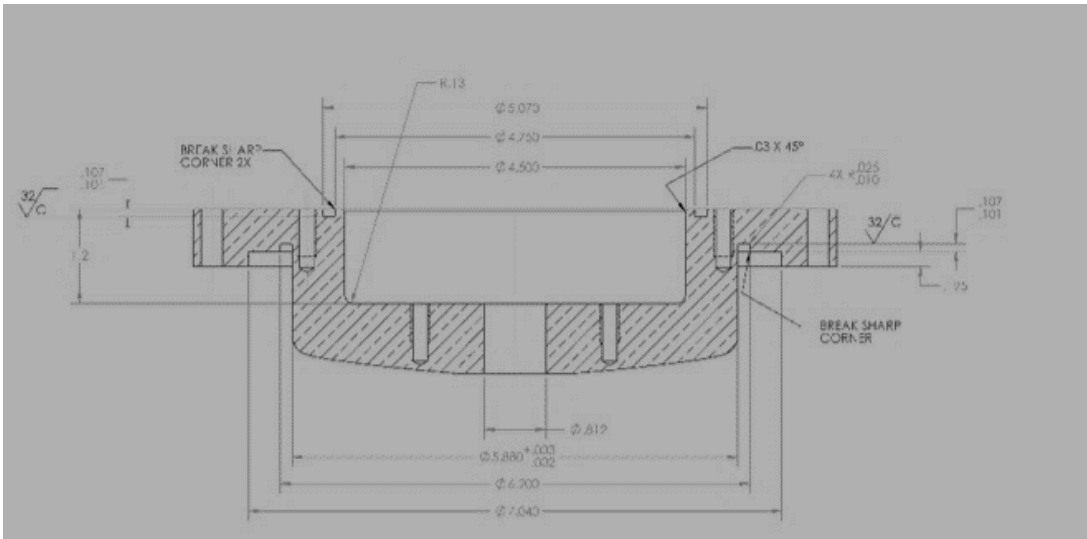


Liner fabrication details

- Glide planes made from brass – designed following the “Atchison” philosophy [6].
- 16 μ -inch surface on liner was specified, but 12 μ -inch was achieved.
- Fabrication drawings located in M-6 files



Liner



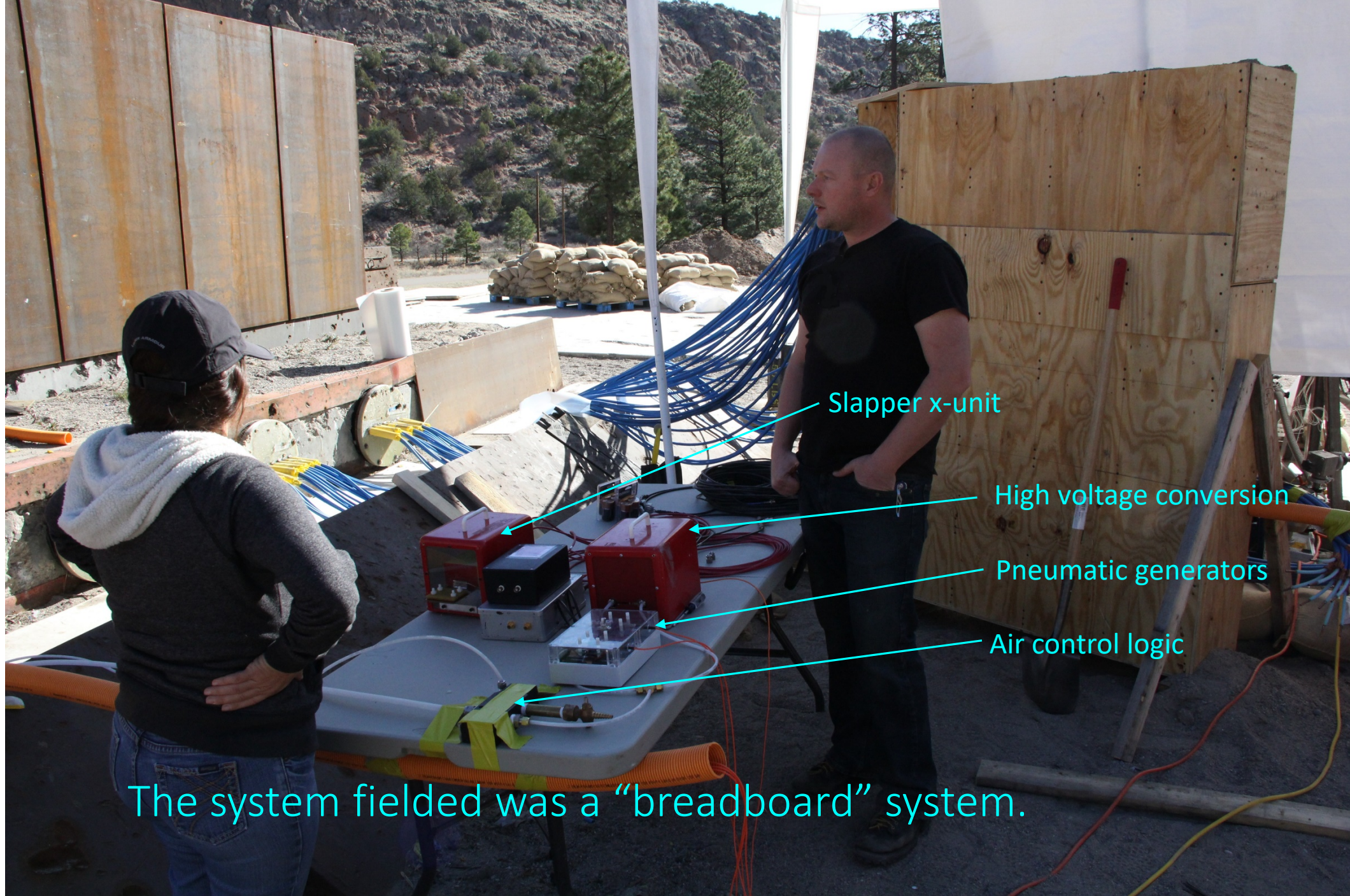
Slapper detonator x-unit

LA-R43S6-L1 employed a unique pneumatic high voltage charging system for the slapper detonator firing unit

To improve confidence that the slapper detonator firing unit was isolated from ground, a pneumatically powered firing unit was developed and fielded on this test.

- Failures experienced in earlier Ranchero History (Rliner-1 and LA-43-1) were traced to inadvertent coupling of slapper detonator firing unit to ground.
- Pneumatically powered generators provided low voltage power with absolutely no ground connection. Voltage was stepped up to final charge voltage (~9kV) using a DC/DC converter.
- The system also provided a very high degree of safety since the air supply could be interlocked inside the bunker.
- The system worked very well, but required a much higher air flow and larger volume than desired. It can be used in any application where volume is not a concern, but will not likely be appropriate for integral-style firing unit where volume is an issue.

The slapper firing unit was the same 1 μ F, 10 kV “Custom” capacitor that has been used for all previous tests with two 24 point 43 cm slapper cables.



The system fielded was a "breadboard" system.

All systems were pre-tested on shot day



X-unit installation ultimately called for slapper cable modifications for future tests due to limited space for slapper cable CVR diagnostics.



The system functioned well, and slapper cable modifications would enable assembly with less arts and crafts.



Slapper x-unit

High voltage supply

Results

Results

- Timing
- Ground plane current sensors
- X-unit performance
- Current measurements
- Wasted Flux analysis
- Faraday rotation current diagnostics
 - FCG input
 - Apex
 - Output transmission line
 - Load groove
- PDV probes measuring R43S6 armature motion
- PDV probes measuring liner motion
 - Summary
 - Layout
 - Raw Data
- Comparison to Roxane run 170509

Event times

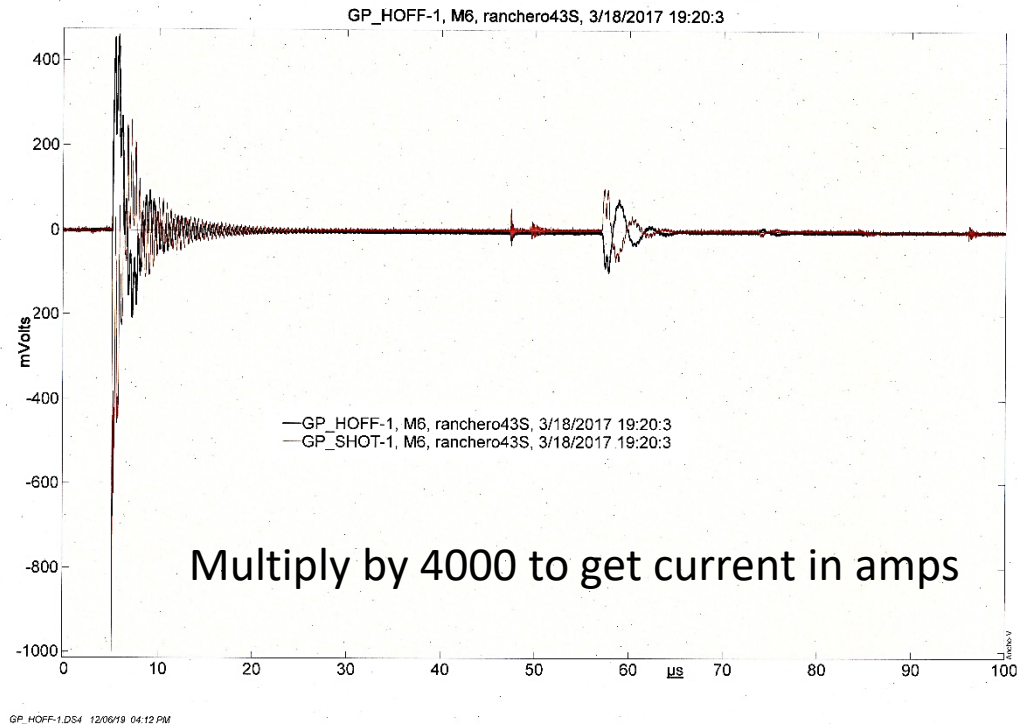
The table gives pertinent event times and relates them to Roxane post-shot calculation 170509, which will be referenced extensively below.

Roxane calculation 170509 is useful for comparison to results. First motion in that calculation is at 53.5 but nearest data dump is 53.9 μs . In the CMU PDV analysis, a better fit between liner motion and PDV data was achieved by synchronizing data and calculation at peak FGC current rather than at FCG first motion.

In 170509, peak current is achieved 29.8 μs after first motion while on experiment peak current is not achieved until 31.36 μs after first motion. However, the time to first motion from initial current was $\sim 1.5 \mu\text{s}$ longer in the calculation, so the total time was very comparable.

Event	time on scope (μs)	comment	Time on Roxane 170509 (μs)	Δt between Roxane and Scopes (μs)
Arog	4.925	DI/dt sensors on individual bank headers, Average is 4.9245	0	4.925
Brog	4.944		0	4.944
Crog	4.915		0	4.915
Drog	4.914		0	4.914
Peak current	88.4		83.3	5.1
Initial current on Rogowski coils	5.08	cable length given approximately by $5.08 - 4.914 = 0.166 \mu\text{s}$	0	5.08
Ranchero armature first motion	57.045	data taken from Rogowski coil/QC time on Roxane is shown to be 53.5, nearest data dump is 53.9	53.5/53.9	3.55/3.15
1E-30 trigger	45.142	fires slapper x-unit shock switch		
Slapper load ring	47.27	From scopes		
Phantom Trigger	-0.029	triggers phantom		
PDV trigger	-0.0305	triggers PDV instruments		
PDV return	0.573			
Faraday trigger	-0.0285	triggers Faraday instruments		
Faraday return	1.604			
Bank triggers	-0.0295	triggers bank switch x-unit		
24-C trigger	-0.0305	Bridgewire for optical fiducial		
				27

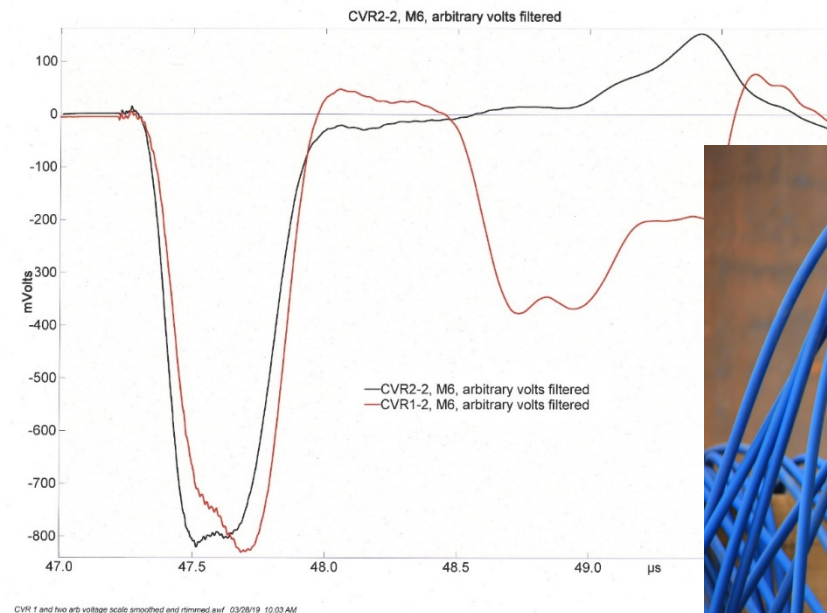
Ground plane current measurements



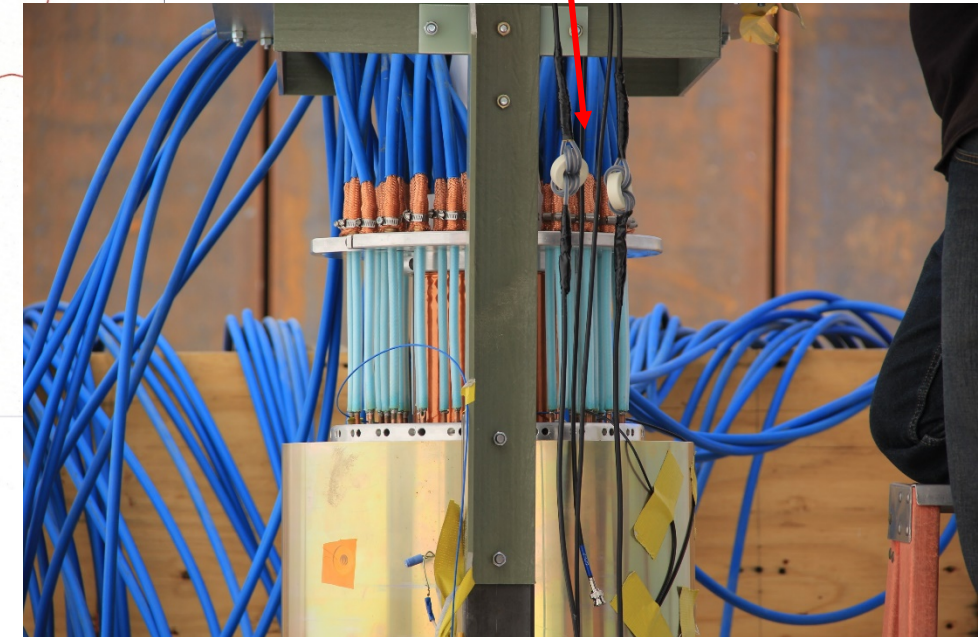
- Ground plane current measurements were made at two locations using Pearson model 1423 current probes
 - Coming out of the common (wipe-off) plate
 - Going into the common plate
 - As seen above, major excursions occur when the bank fires ($\sim 5 \mu\text{s}$) and also when Rancho fires ($\sim 57 \mu\text{s}$)
 - Excursion at 57 is about 400 A.
 - No ground loops were noticeable on the scope traces
- Signals were terminated in 50Ω at the scopes and had a two way balanced tee.
 - 0.0005 V/Amp terminated
 - Balanced tee divides signal by 2.

Ranchero FCGs are initiated by firing two detonators which actuate a shock switch that triggers the slapper x-unit. Current through the slappers is monitored by current viewing resistors (CVRs), one in each cable. CVR-1 and -2 are shown with arbitrary voltages. CVR signals were monitored through isolation transformers which were not calibrated, and signals are scaled to compare burst times easily.

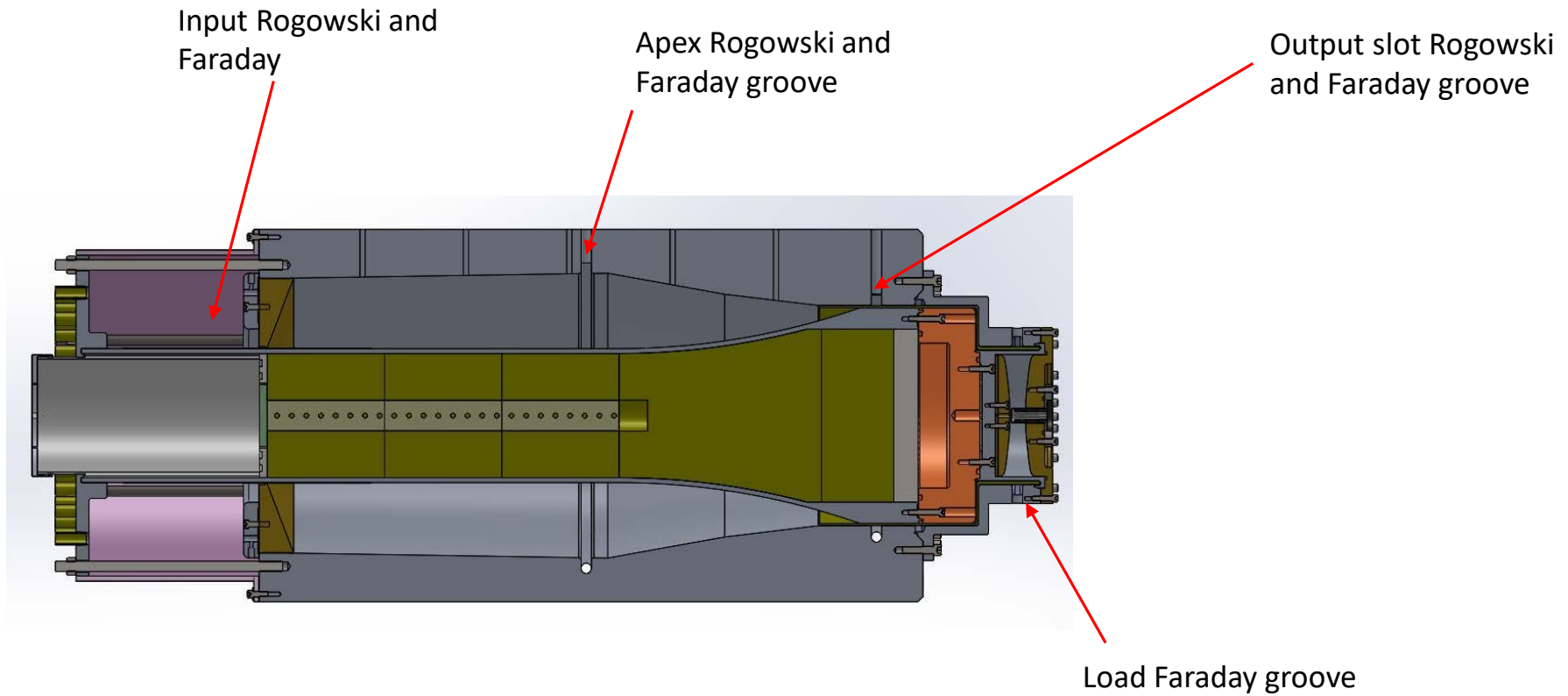
- Burst time on cable 1 is at 47.514
- Burst on cable 2 is more subject to interpretation, but one can choose 47.542
- The cable resistances for the two slapper cables were carefully matched, but the values were not recorded.



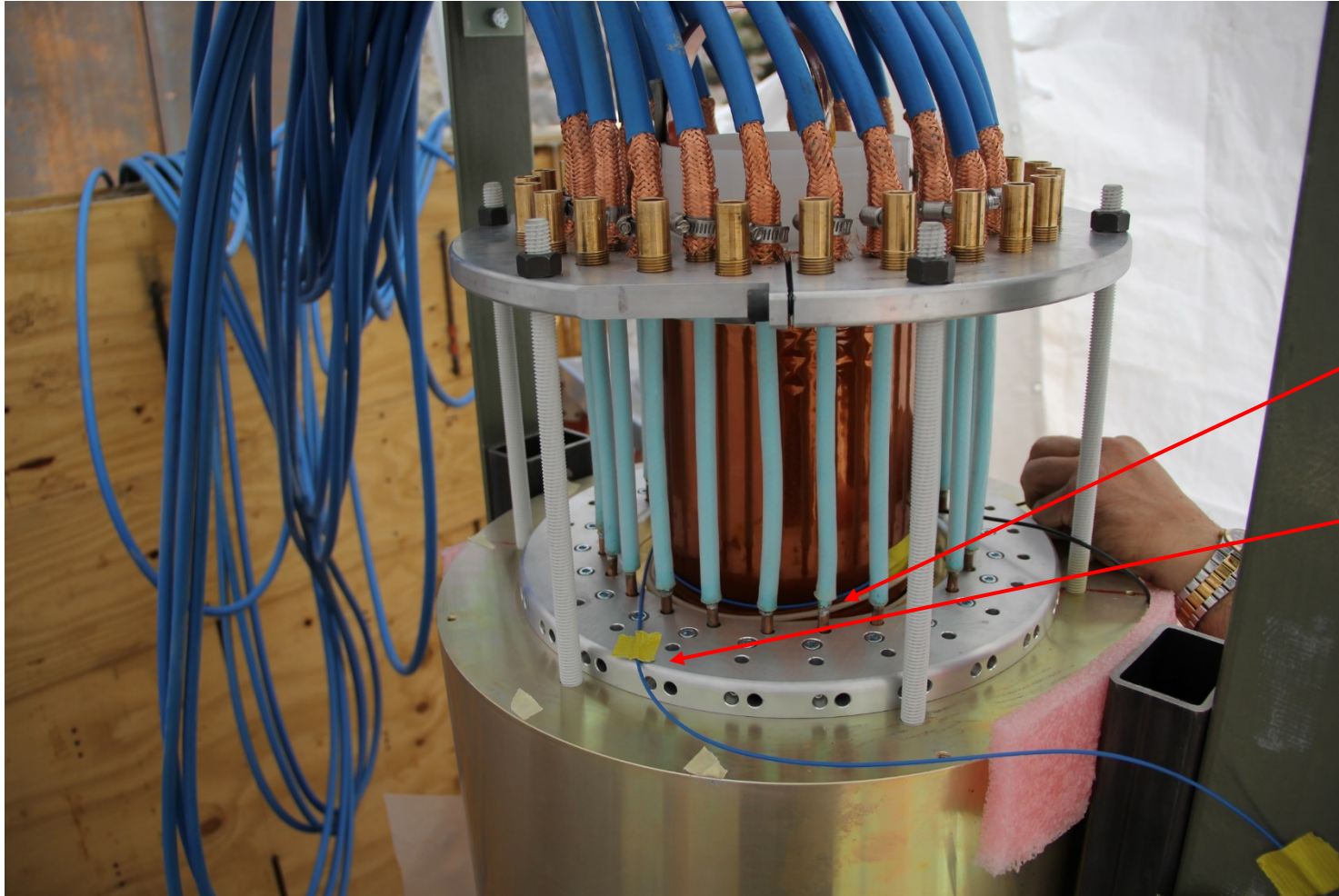
CVR ground isolation transformers



System current measurements

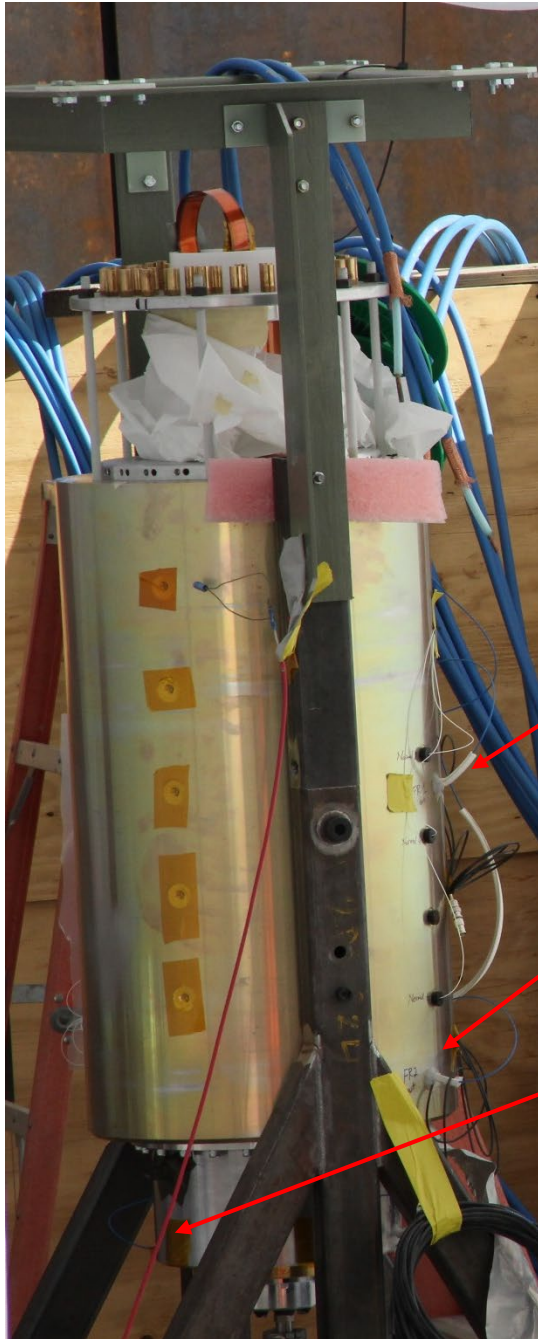


Input current hookup



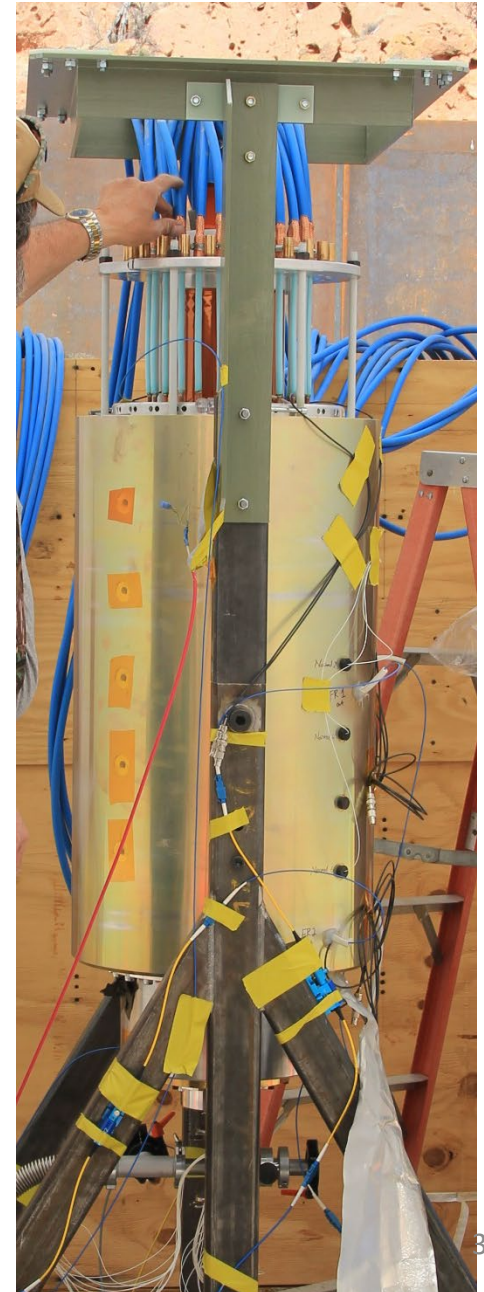
- Rogowski coils

- Faraday probe
(fiber was not sufficiently protected, and no useful data resulted)



Apex, Output, and Load
Rogowski and Faraday
sensor locations

- Apex
- Output
- Load (Faraday Only)



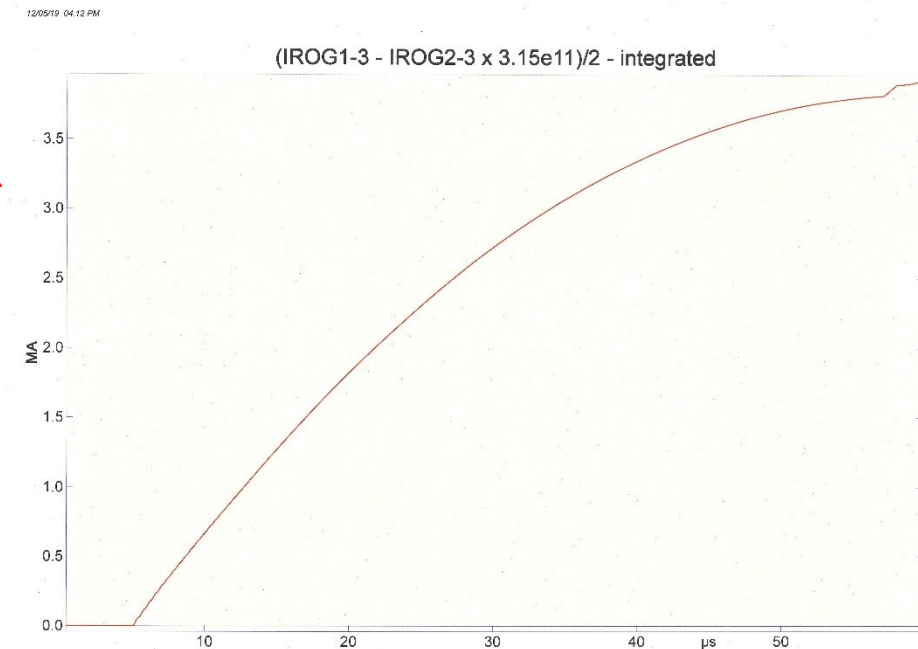
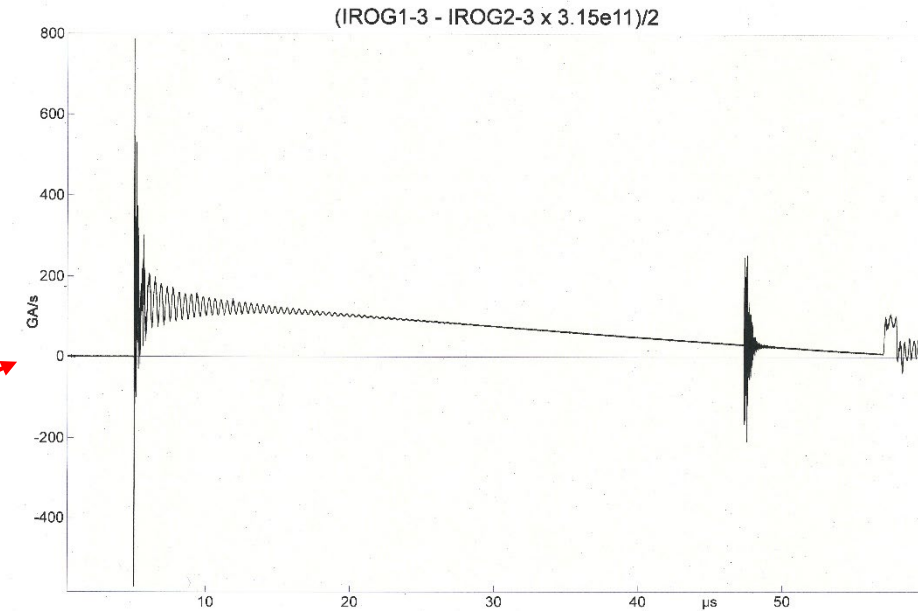
Current measurements

- Initial calibration assumptions for system current measurements were not born out, and considerable effort went into determining the best calibration factors to use. Ultimately calibrations were established from averaging initial current values and considering RLC determinations from bank.
 - Using the Faraday analysis by Hank Oona, the currents in the table below were determined.
 - The Faraday overlap was determined to be as shown in the table, and corrected initial currents are shown
 - Nominal Rogowski coil calibrations were applied to give the values shown
 - The global average of Rogowskis and Faradays is 3.51 MA
- Applying our Best RLC values for the bank and the applied voltage on the modules, the calculated seed current was 3.52 MA (See [Comparison of LA43S_L1 data and Roxane Postshot Simulations] Bob Watt 170525) in M-6 shared drive folder.
- We have taken the initial current for all further analysis to be 3.5 MA

groove	diagnostic	Initial current (MA)	Faraday overlap	Corrected Faraday current	diagnostic	Initial current (MA)	
apex of armature	Faraday 1 from Hank	3.69	1.11	3.34	Average of 2 Middle Rogowski coils	3.57	
output slot	Faraday 2 from Hank	3.78	1.09	3.46	Average of 2 Output Rogowski coils	3.35	
load groove	Faraday 3 from Hank	3.80	1.07	3.54			
input slot	FR 4 not interpretable				Average of 2 input Rogowski coils	3.80	
		11.27		10.34		10.72	
average		3.76		3.45		3.57	
average of corrected faraday and nominal Rogowskis							3.509365

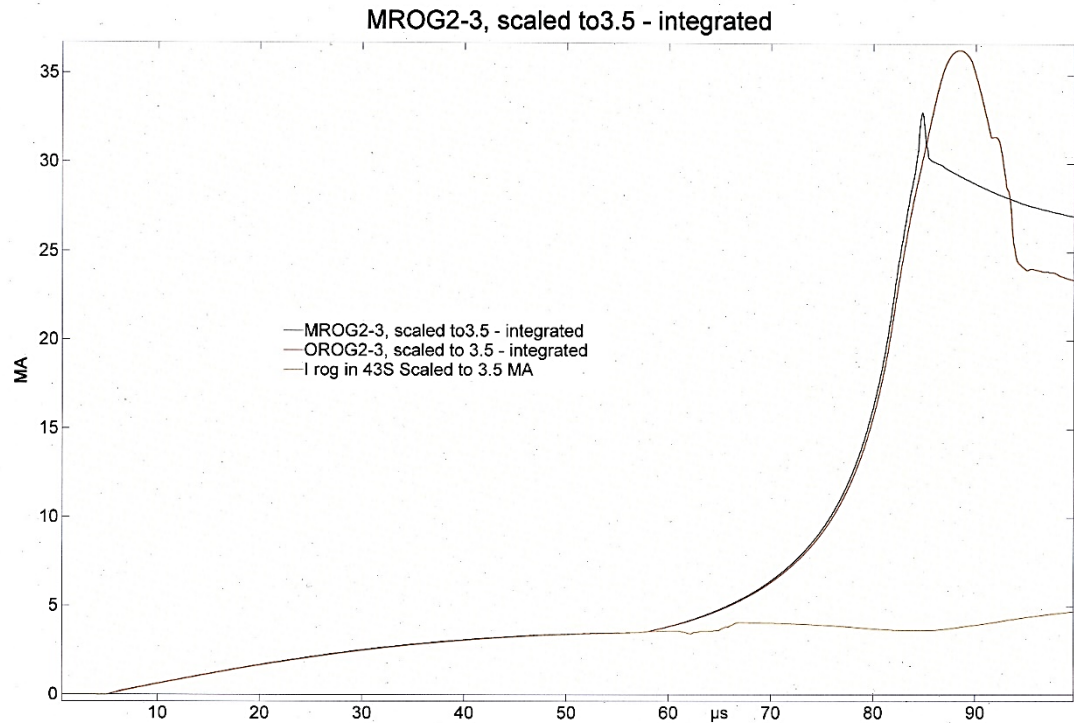
Input Rogowski data

- Input Rogowski coil data.
- The di/dt curve is the result of subtracting a negatively recorded probe from a positively recorded probe, then dividing by two.
- Nominal calibrations are applied
- The di/dt curve is then integrated numerically to obtain I .
- The raw result here shows a peak curve of 3.8 MA.
- When pooled with all other current sensors, the value of 3.5 MA was chosen as the most accurate initial current for the test, and all current sensors were calibrated to that value.

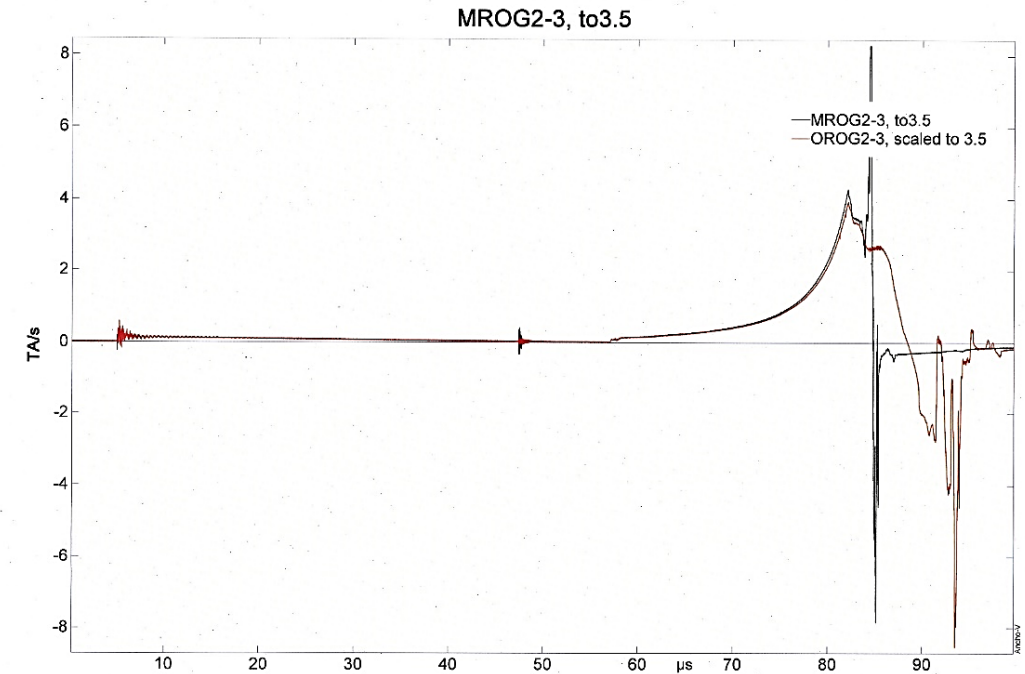


Currents from Rogowski coils scaled to 3.5 MA initial current

- Final determination is that initial current is 3.5 MA as stated above.
- Current for all three Rogowski coil sets (Input, Middle and Output) are shown below, forced to agree at 3.5 MA at 57 μs .
- Idot for Middle and Output coils are shown to the right.
- The baselines are zeroed on both signals prior to bank switch closure, and the difference seen between the probes as time increases suggests a possible tilt in the baseline.



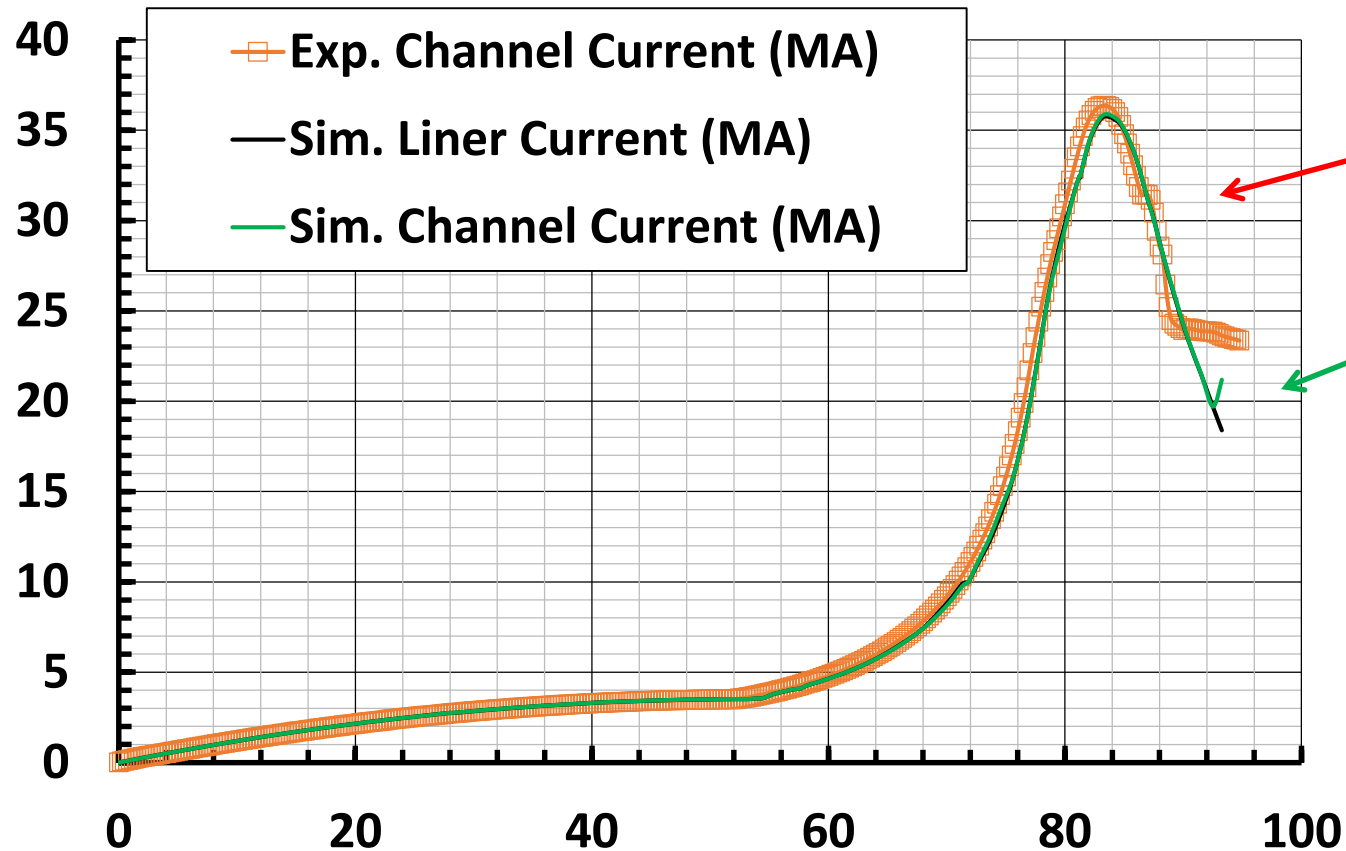
01/23/19 10:01 AM



AE28A78F4ECF46daADB0067395E7DFCE.M and O rog scaled to 3.81 from I rog avf. 01/23/19 10:01 AM

From Appendix III [Comparison of LA43S_L1 data and Roxane Postshot Simulations] post-shot Roxane calculations in shared drive; Using the Pt. 88 setup parameters, the Roxane simulation with Ohmic heating (OH) agreed quite well with the experiment current trace in the channel.

[Note that FCG start in calculation is 53.5 μ s in simulation, but 52 μ s in data. See notes in “event timing” above. In the CMU PDV analysis below there is an attempt to synchronize liner position in the experiment with position in this calculation. The best agreement goes with synchronizing data with calculation at peak current. In actuality, the initial current pulse is 1.5 μ s longer in the calculation, but the FCG function time is longer by the same amount in the experiment.

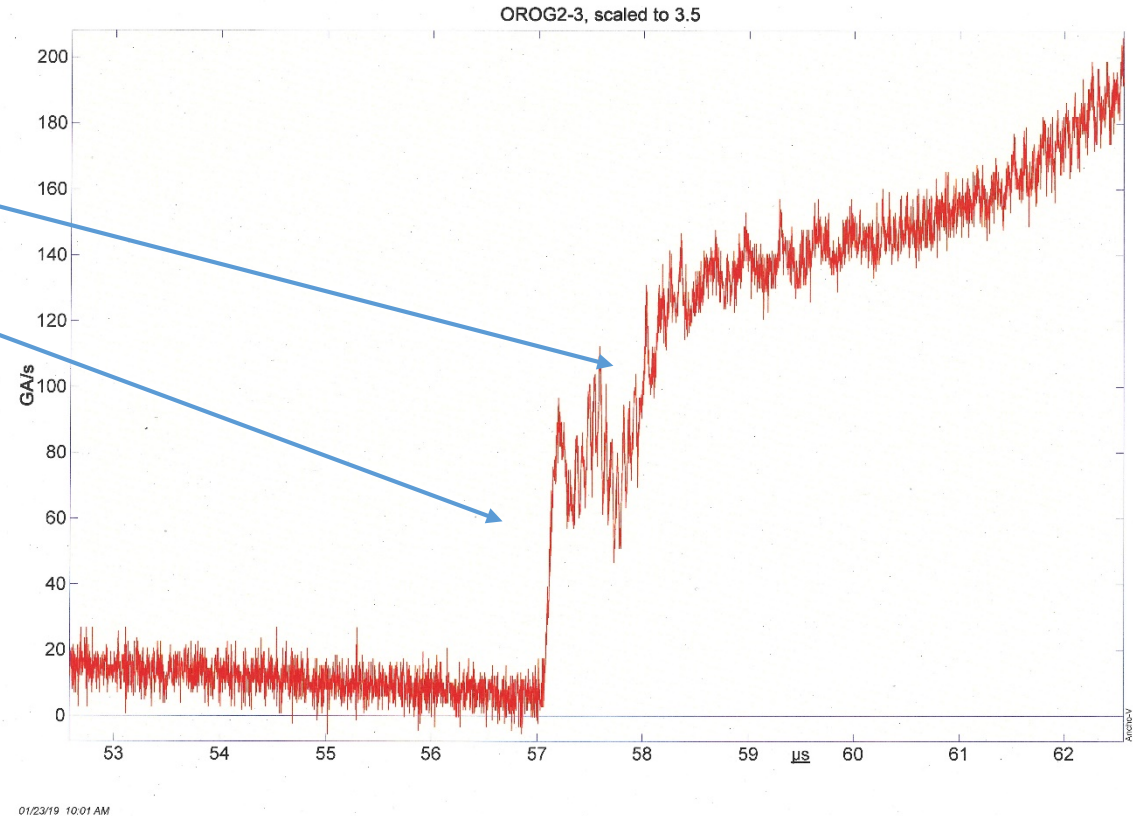


Note the FR groove closure artifact in the simulation at 92 μ s and what might be the same effect in the data at \sim 89 μ s.

The FR groove in the main FCG closes prior to peak current and flux compression is seen in the little void thus formed. (Vertex current is not shown here but look in the earlier section).

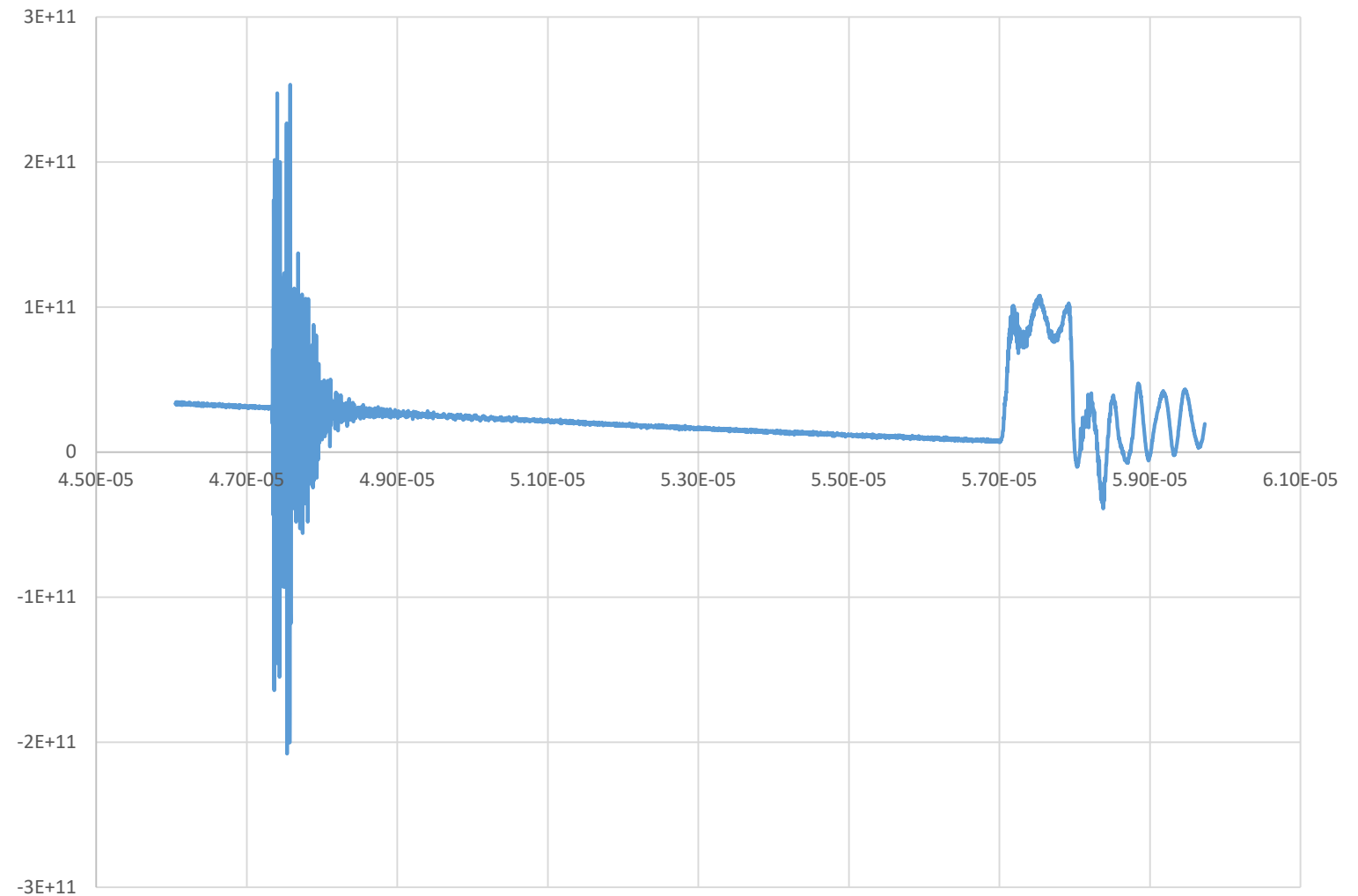
di/dt trace shows characteristic double step at first motion/crowbar

- Crowbar
- First motion of armature
- Delay from first motion to crowbar is $\sim 1 \mu\text{s}$, which is longer than usual. It was discovered post-shot that there was a larger than normal gap between the armature and the glide plane, which explains the extra delay.



di/dt at crowbar time as seen on the input Rogowski coil (4-2-20)

It is possible that the quality of the short at crowbar as viewed by the input Rogowski coil is better than seen from inside the generator. This was noted in design discussions during the spring of 2020 for the first boosted R43S6 test. The signal shows first motion at $57\text{ }\mu\text{s}$ and actual crowbar at $58\text{ }\mu\text{s}$. This is noted for future observation, and as it pertains to MHD modeling of the FCG.

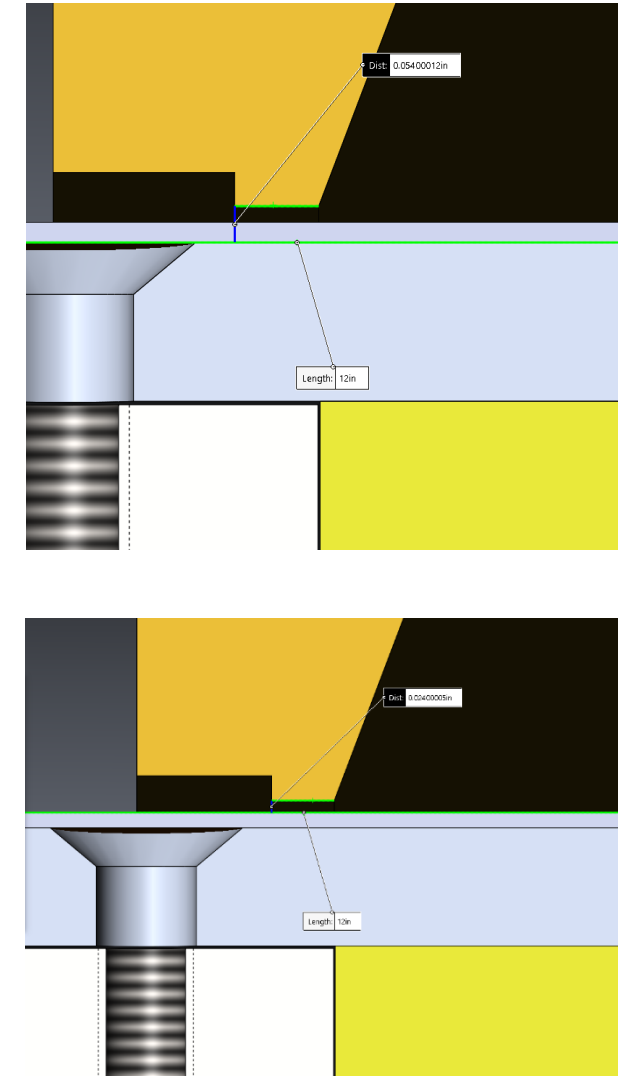


Armature-Input glide plane gap

- From Ranchero Drawings dated 6/22/15
- Glide plane diameter
 - Max = 6.585 (167.26 mm)
 - Min = 6.575" (167.01mm)
 - Nominal = 6.589" (167.13)
- Armature OD
 - Max = 6.502" (165.15 mm)
 - Min = 6.483" (164.67 mm)
 - Nom = 6.4905" (164.86 mm)
- Gap
 - Max = 0.052" (1.295 mm)
 - Min = 0.0365" (0.927 mm)
 - Nom = 0.04925" (1.251 mm)

Dimensions from William 2/21 indicate the gap was nominally 0.078" (1.98 mm)

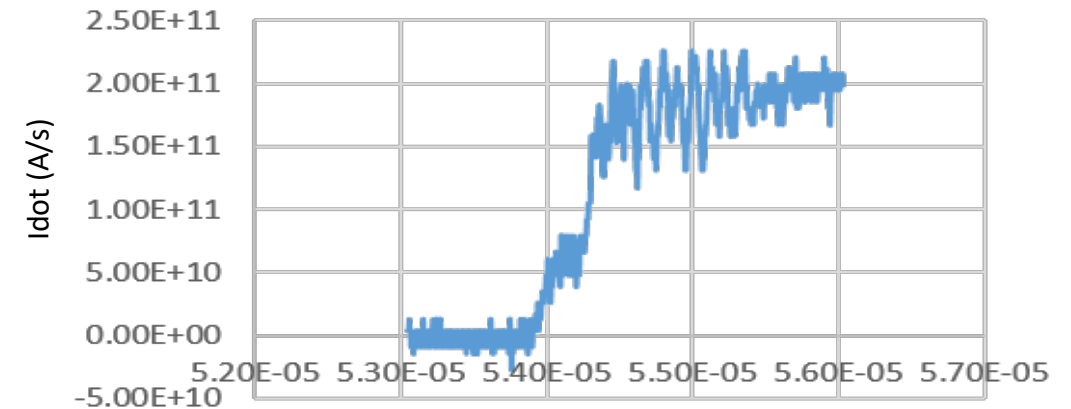
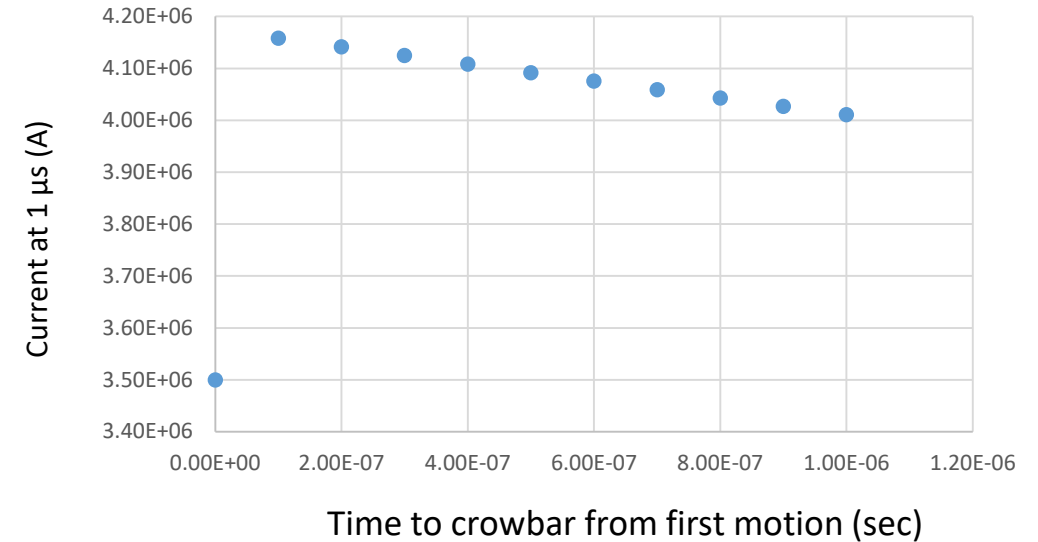
These two sets of dimensions are found in pre-shot documentation. Based on the difference in first motion to crowbar times seen on earlier shots vs this shot, it is likely that the dimensions were changed to the larger gap before R43S6-L1 was manufactured. The designer who produced both sets of drawings has retired and since we will proceed with the new dimensions in the future, we will not pursue the original reason for the change. The difference between nominal dimensions does not quite account for the difference, but issues such as centering of the armature in the glide plane could easily make up the difference.



Delay in crowbar time diminishes peak current

- Crude computation based on perfect flux compression in the coaxial section for 1 μ s shows the decrease in gain due to the capacitor bank remaining in the circuit until crowbar time.
 - 3.5 MA initial current
 - 52 nH is in the capacitor bank circuit until crowbar.
 - Load for all time is 2.5 nH
- Calculation shows the current for each case at 1 μ s after first motion as a function of time to crowbar from first motion.
- First motion is at time zero
- Early Ranchero tests [LA-43-2 and REOT-2] had an average time to crowbar from first motion of ~ 320 ns.
 - At 320 ns, the calculated current is roughly 4.1 MA.
 - At 1 μ s, the current is ~ 4 MA
 - A 1 μ s, the current is 100 kA less if than is the crowbar time than it would have been if crowbar had occurred at 0.32.
- Since the gain of the generator was ~ 10 , peak current would have been about 1 MA higher if crowbar had occurred at 0.32
- The gain calculated in this simplified way is higher than actual. On the shot, the current went to 3.6 MA, not 4.
 - There is 2.5 m Ω in the capacitor bank circuit which is not reflected in the calculation.
 - At 3.5 MA, 2.5 m Ω will dissipate 8.75 mWeb in 1 μ s. In a 140 nH circuit, that is another ~ 60 kA loss.
 - Some flux is also lost to recharging the bank, but zero order approximations suggest that is only ~ 2 kA.
- The data show that the current at crowbar on R43S6-L1, which is 1 μ s after first motion, is 3.6 MA. Adding estimated resistive losses and losses due to recharging the bank would lower the difference from the crude model to ~ 300 kA.
- The larger delay experienced on LA-R43S6-L1 caused a decrease in peak experimental current of less than 1 MA. It is, nevertheless, true for the future that getting the cables and capacitor bank out of the circuit as soon as possible is prudent.
- The same crude tool has been used to show that a booster FCG, such as the MK-X, reduces the lost flux even more because it has much less inductance at Ranchero crowbar time. In addition, if a system couples current directly to the Ranchero, rather than coupling through cables, the losses are even less.

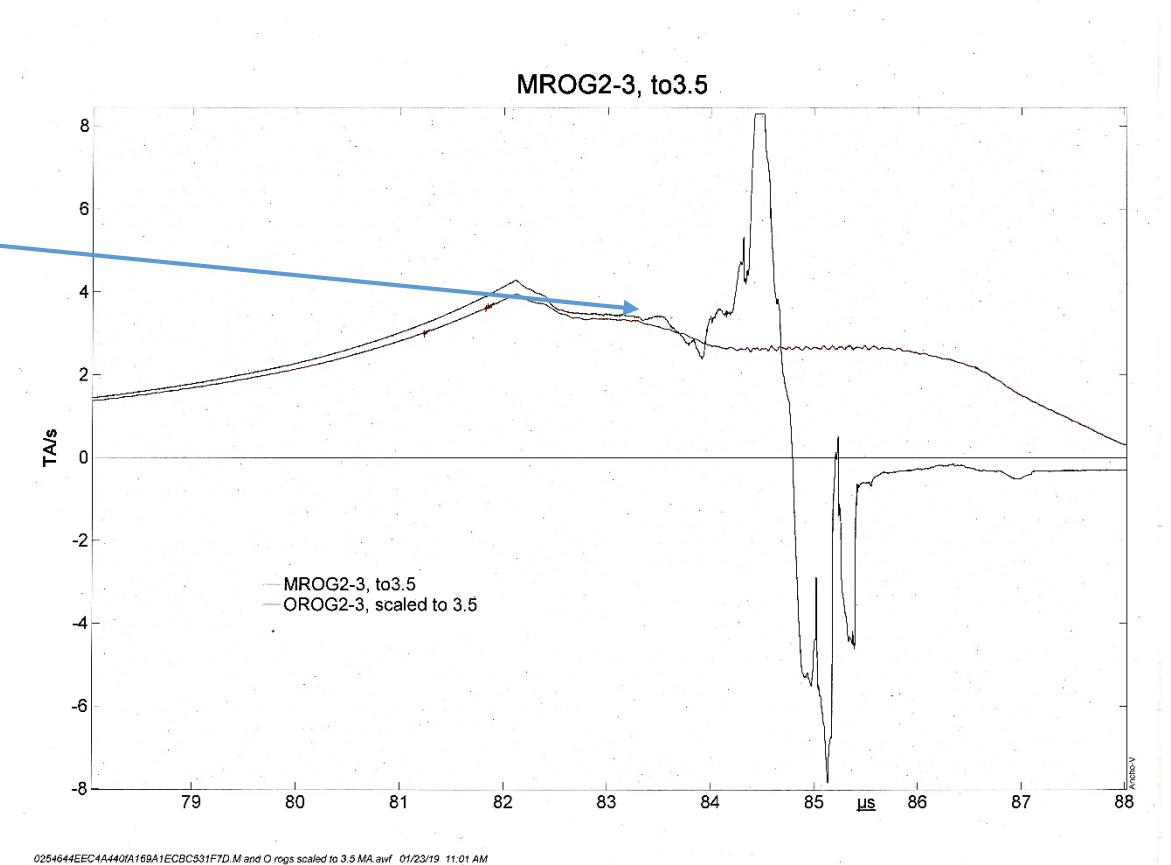
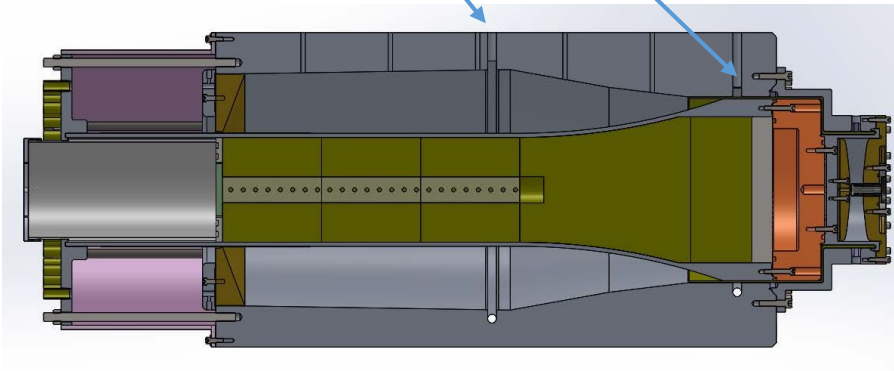
Current at delayed crowbar time



This is crowbar Idot from LA-43-2. The same events that took 1 μ s on LA-R43S6-L1 took 350 ns on this shot. Discussions for future Ranchero designs uncovered the larger armature/glideplane gap dimension, but the resulting losses have been deemed an acceptable compromise between performance and ease of assembly.

Idots near peak show impact of armature at apex versus the output slot

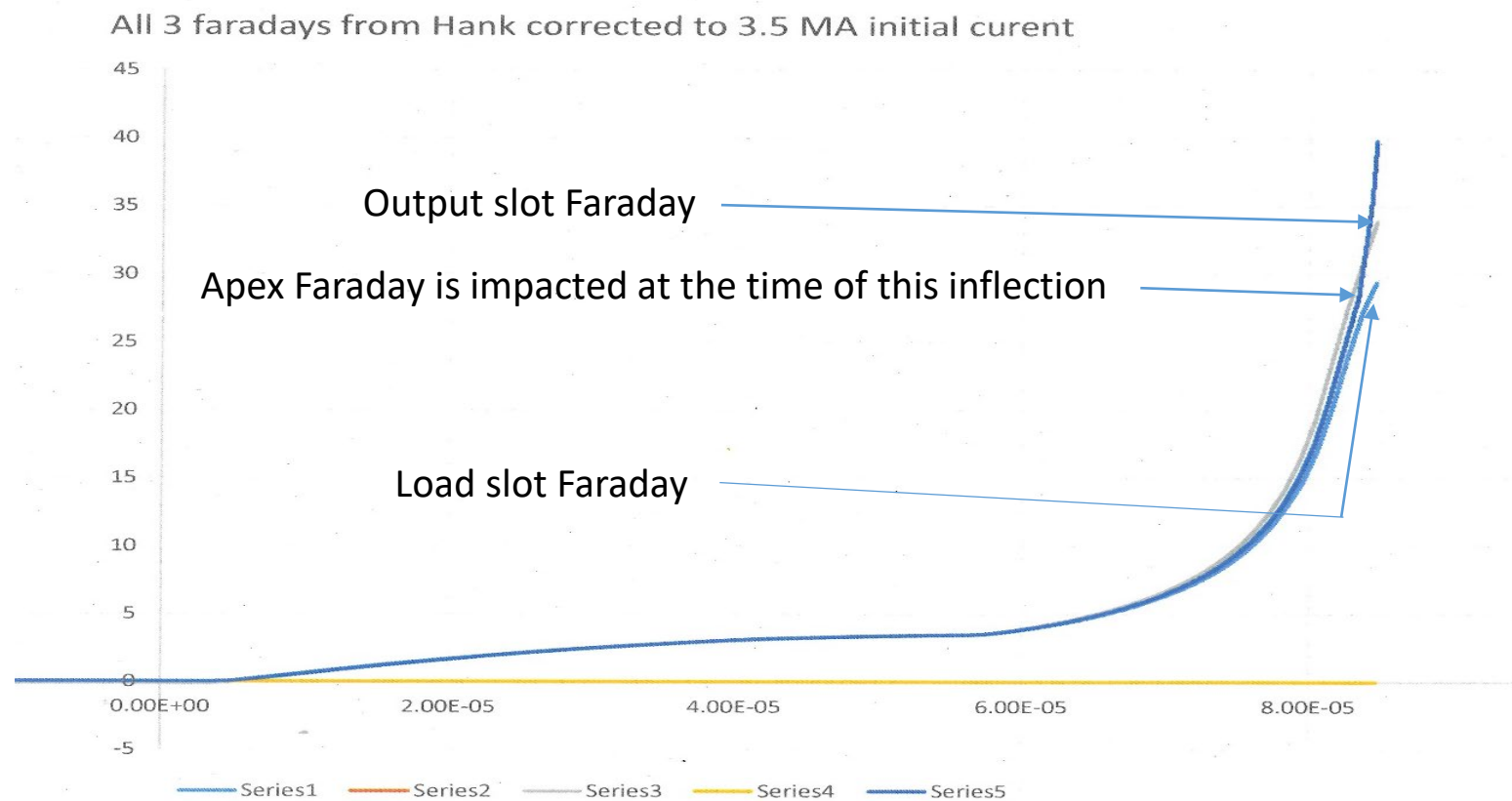
- Armature impact at apex
- Output probe
- Apex probe



MROG is the probe in the Apex and OROG is the probe in the output slot

Faraday rotation current measurements did not survive to peak current. Interpretation towards end of record were suspect

- Initial interpretation for I_0 with overlap correction at 57 μs .
 - Faraday 1 (Apex); 3.34 MA
 - Faraday 2 (Output slot); 3.46
 - Faraday 3 (Load slot); 3.54 MA
- Plots are corrected to be 3.5 MA at 57 μs .
- Faraday 2 has the value of 33.7 MA at 84.7 μs compared to 29.9 MA at this time on output slot Rogowski, which peaks at 36.4 at 86.3 μs .
- Faraday 3 is 29.3 at this time.
- At the time of the inflection due to impact (84 μs), the values are:
 - FR1; 35.2
 - FR2; 32.8
 - FR3; 28.7
 - Output slot Rog; 28
 - Apex Rog; 29.3
- The Faraday rotation probes in the load groove did not survive for a different reason. Pre-shot calculations showed that the magnetic field destroyed anything in this groove during times of interest, but it was not noted until after the shot.

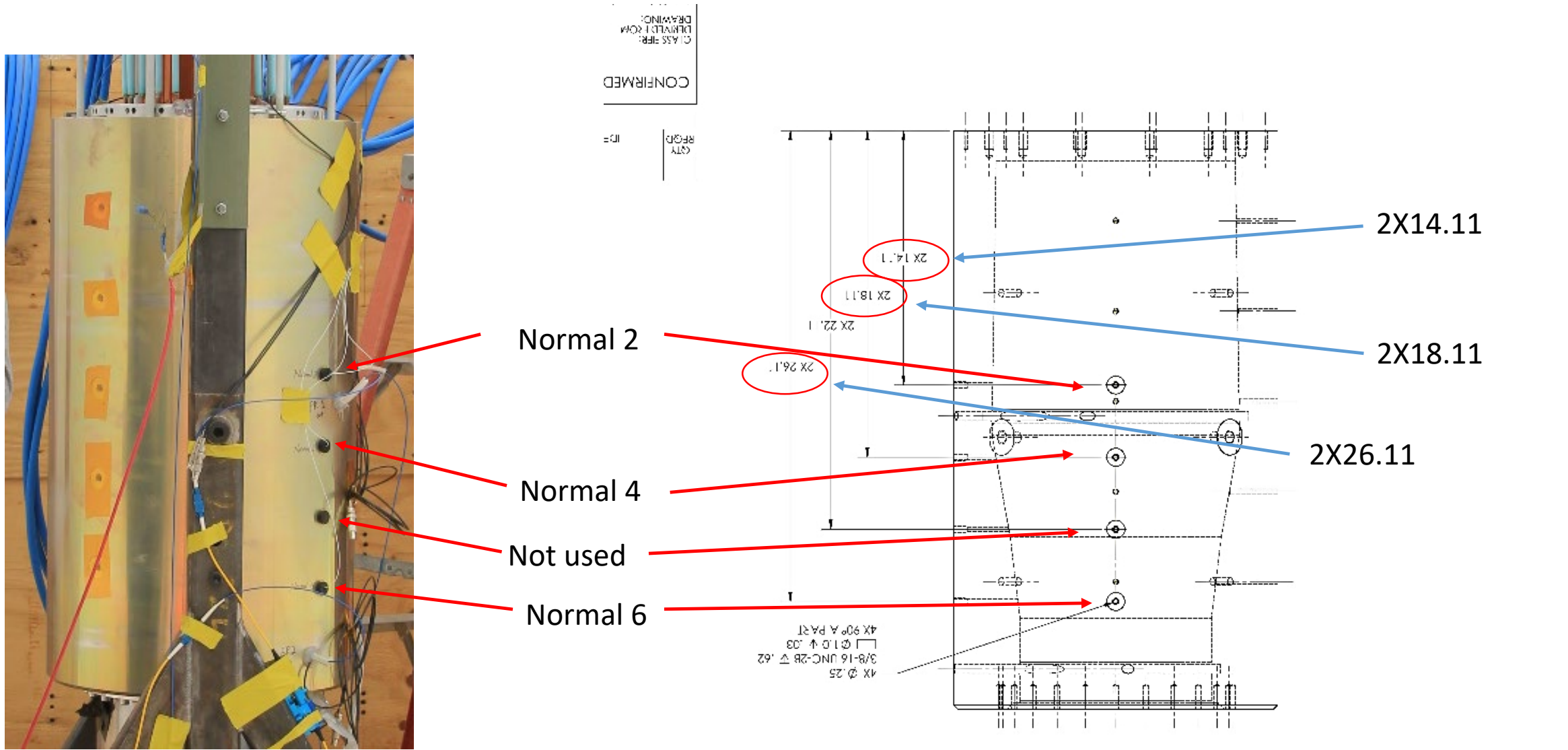


Wasted flux estimate-Goforth

- ~5.7 nH/m residual inductance seems to be a good average for Ranchero FCGs with tapered armatures.
 - For example, LA-43-2 had a residual inductance of 2.28 nH with a stator length of ~40 cm. This includes diffusion and insulation, which was initially 0.5 mm polyethylene.
 - For this test: LA-R43S6-L1 went from 3.5 MA to 36.4. The FCG was 86 nH originally and the load 2.5 nH. Post shot, the load had grown to 3.9 nH, so pure flux conservation indicates the final inductance was 8.5 nH. Minus the measured load inductance of 3.9 nH (initial inductance plus position indicated at peak current by PDVs), there is 4.6 nH left. An “eyeball” estimate of a Watt MHD run shows that there is still a gap of maybe 2 mm over a length of 6” at peak current. At that radius, that would amount to 0.5 nH, leaving the waste L to be 4.1 nH. I estimate the effective length of the stator to be ~69 cm. So, .69 m X 5.7 nH/m = 3.9 nH. The difference between 4.1 and 3.9 is better than the quality of my estimates, and it appears that the swooped Ranchero has wasted inductance very similar to the slightly tapered pure coaxial Rancheros.

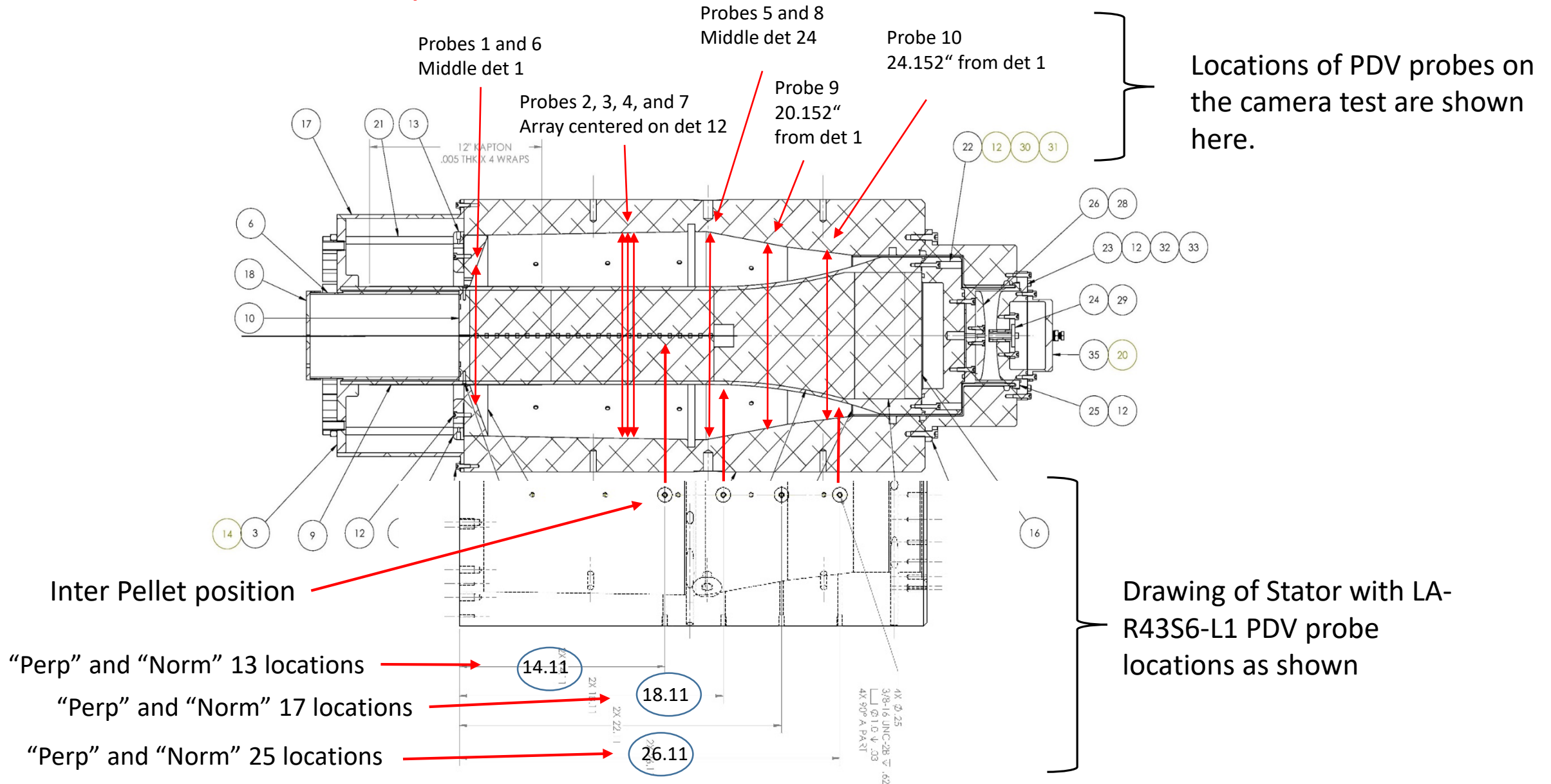
Armature PDV measurements

PDV probes monitored armature velocity at 3 z-locations and 2 azimuths



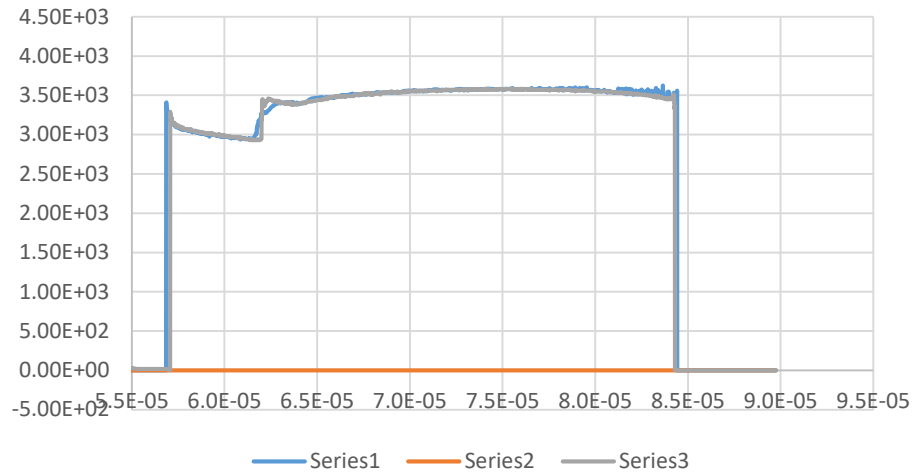
Drawing is shown upside down to compare to the shot orientation

Z location of the PDV probes on LA-43-S-CT and LA-43-S assemblies

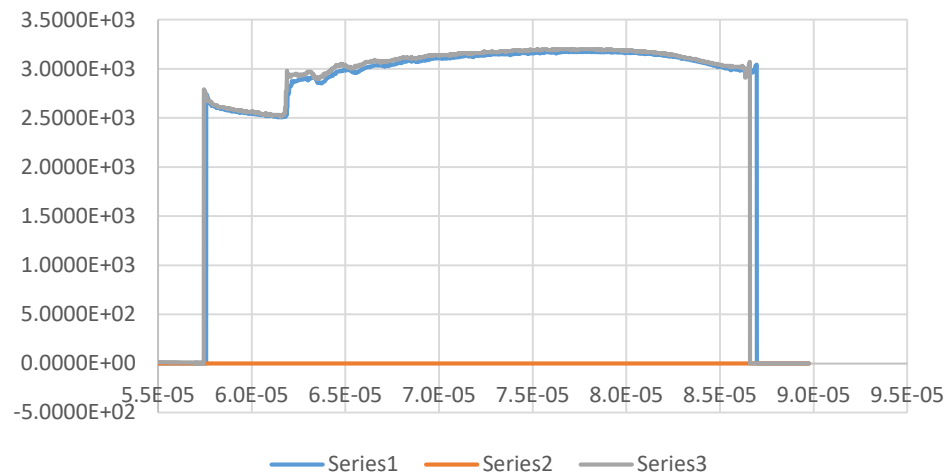


PDV data were obtained at 3 positions along the axis and at two azimuths. The “Norm” signals looked straight down onto pellets and the “perp” probes looked at 90° to that direction

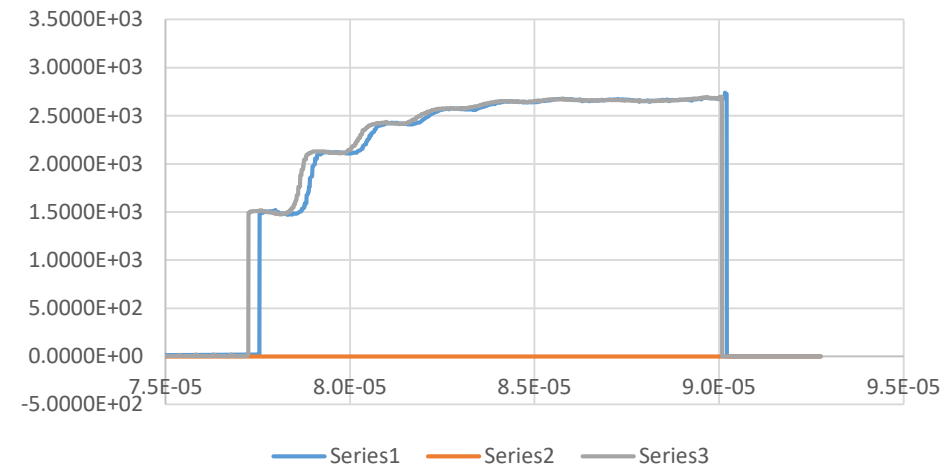
Norm and Perp 13 43S-L1



Perp and Norm 17

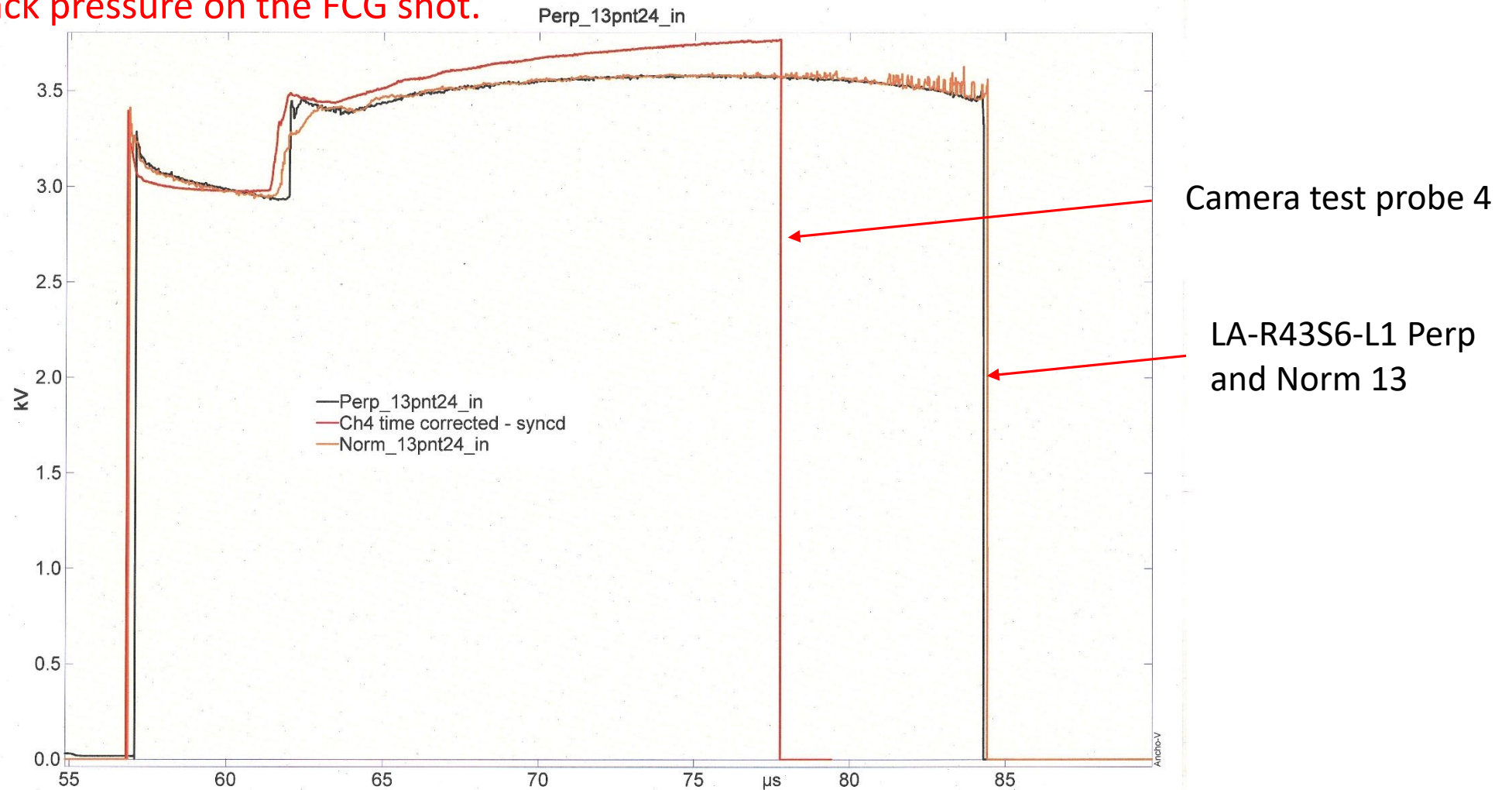


Norm and Perp 25

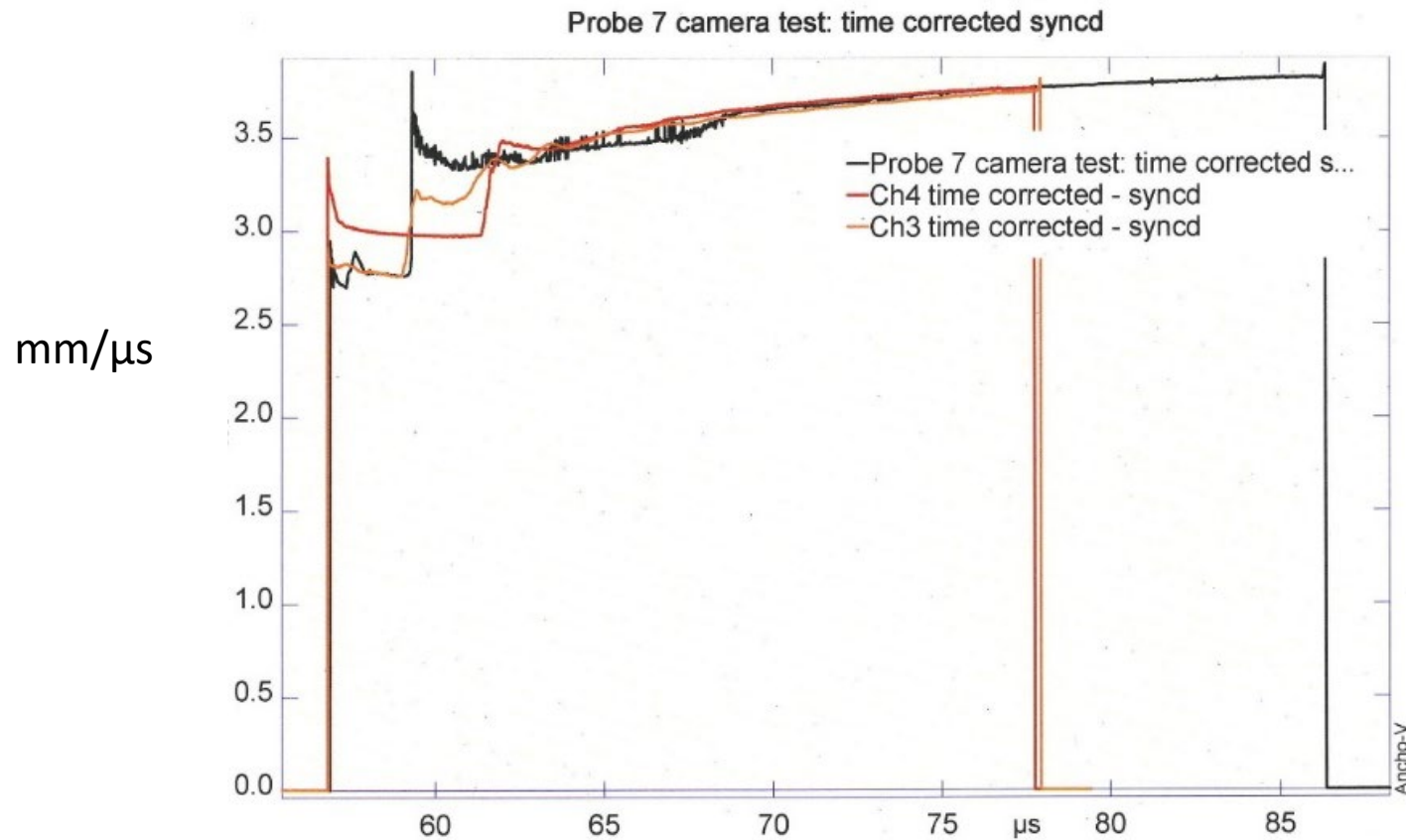


It is possible that there was a slight misalignment of these probes, and timing is very sensitive to position along the swoop. This may have lead to this amount of difference in initial motion.

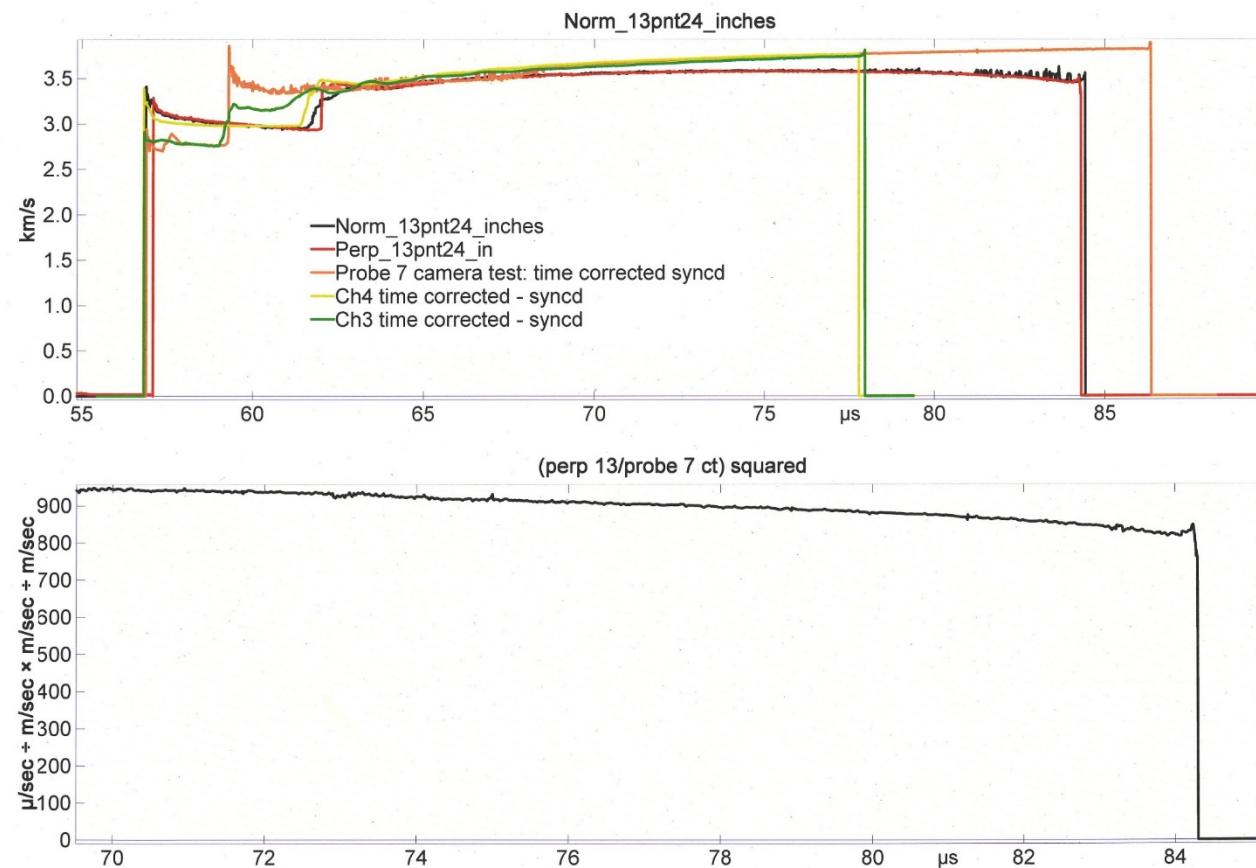
Comparison of Probe 4 from the Camera test with PDV probes in the “13” location on R43S6-L1 confirms that these probes are in the same location relative to detonator point locations. This has been identified as an inter-pellet position. Velocity difference between the two tests is due to the magnetic back pressure on the FCG shot.



Probe 7 on the camera test recorded data for a longer time. These traces show that after recollection, probe 7 is the same as probes 3 and 4.

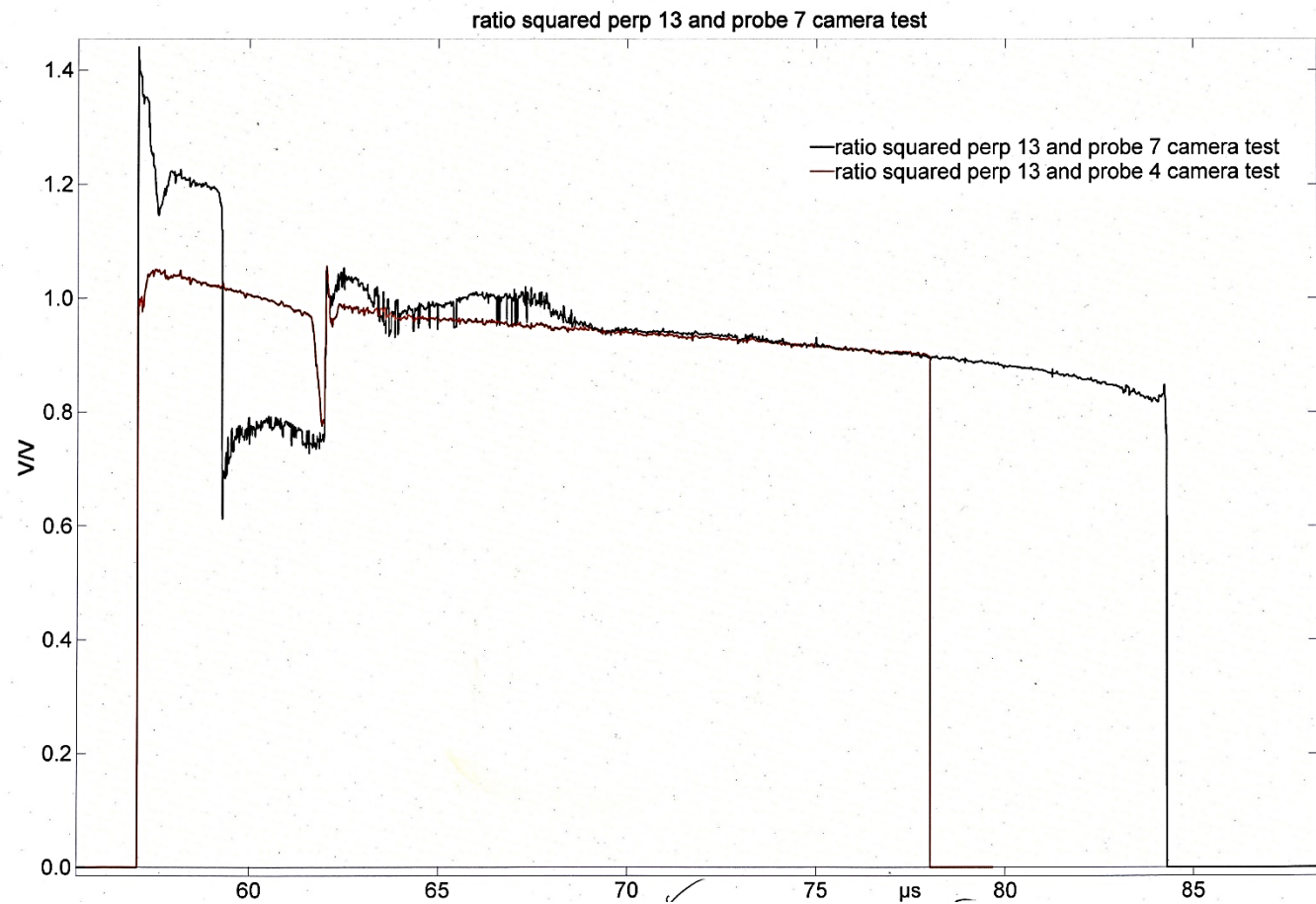


Some information about the influence of the magnetic back pressure is shown here. One can see the decrease in armature KE at one point by taking the ratio of velocity of the R43S6 armature and the camera test at similar points and squaring the ratio.



At this location along the armature, ~20 % of the armature kinetic energy has been extracted by the magnetic field at 84 μs (4 μs prior to peak current).

This figure shows the ratios squared of “Perp 13” to both probe 4 and probe 7 from the camera test. The results are consistent.



CMU PDV measurements summary – data follow

Eleven of 12 PDV probes intended to record the implosion of the liner returned data. All probes looked from points just inside the outer wall of the central measuring unit (CMU), which had a radius of 1 cm, and located half way between the two glide planes. Four probes looked radially outward, and four each looked at + and - 10° angles. During the analysis it was noted that prior to the shot, the meaning of plus and minus had not been specified, but assembly photographs allowed the actual orientation to be determined. Minus angles were along a line angled toward the outer glide plane and plus angles were toward the inner glide plane.

The records from the radially inward (0°) probes give a clear picture. Analysis shown below indicates that by impact with the CMU, the implosion center was ~2.13 mm off center, and the probes followed the implosion to a point ~1.5 mm from the outer wall of the CMU. Since the implosion was off center, probes viewing the liner in a location that hit the CMU early recorded smaller velocities and less total displacement than the probes on the opposite side. The location of the center was determined initially by finding a point from which a circle could be drawn through all four late time points. It was then noted that if we assumed that the probes lost signal at the same position with respect to the CMU wall, the same point could be found by assuming the center was half way between the final displacement measured for opposing probes. Likewise, assuming 10 mm/μs implosion speed, the arrival time was adjusted and it brought the arrival time at the 10 cm circle with the skewed center to within 147 ns for all four points. The implosion was circular, just off center. With the assumptions that the probes fail just before contact with the CMU, we can say that due to the 2 mm offset, the liner hit the CMU 570 ns earlier on one side than the other. From MHD calculations below, this liner is about 1.5 cm thick at impact. If the shock running backward from the impact goes 2 cm/μs, then the duration of the shock would be ~1.5 μs.

Angled probes require more consideration. The straightforward analysis suggests that the performance of the liner was very different along one glide plane. However, a good model for the data suggest that the center of the CMU probe array was likely shifted in the z direction toward the FCG by approximately 1 mm. With this assumption, the angled probes agree very well with the MHD calculation presented here, and also with the off center implosion. That analysis is on pages 85 to 89.

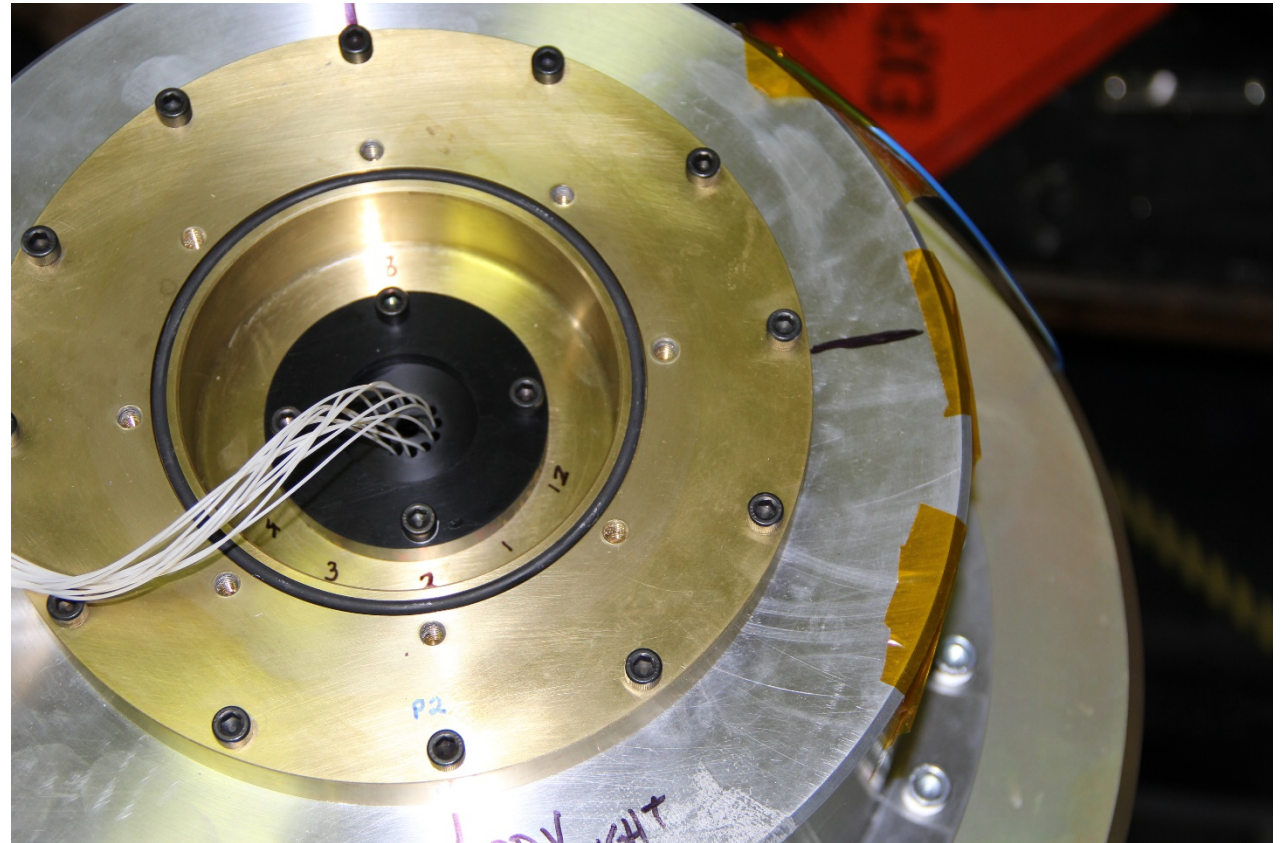
PDV installation into load in building 111



Installation complete
and assembly is inverted

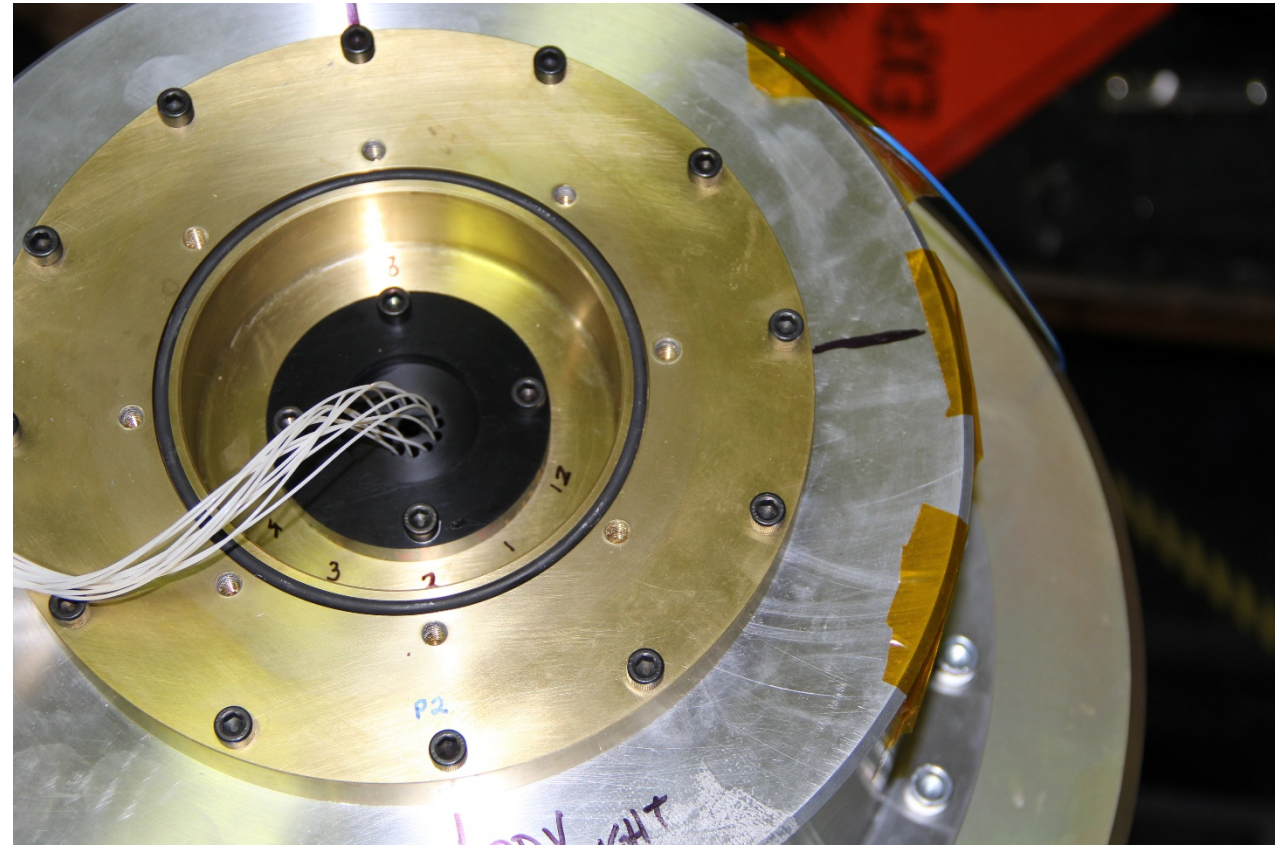
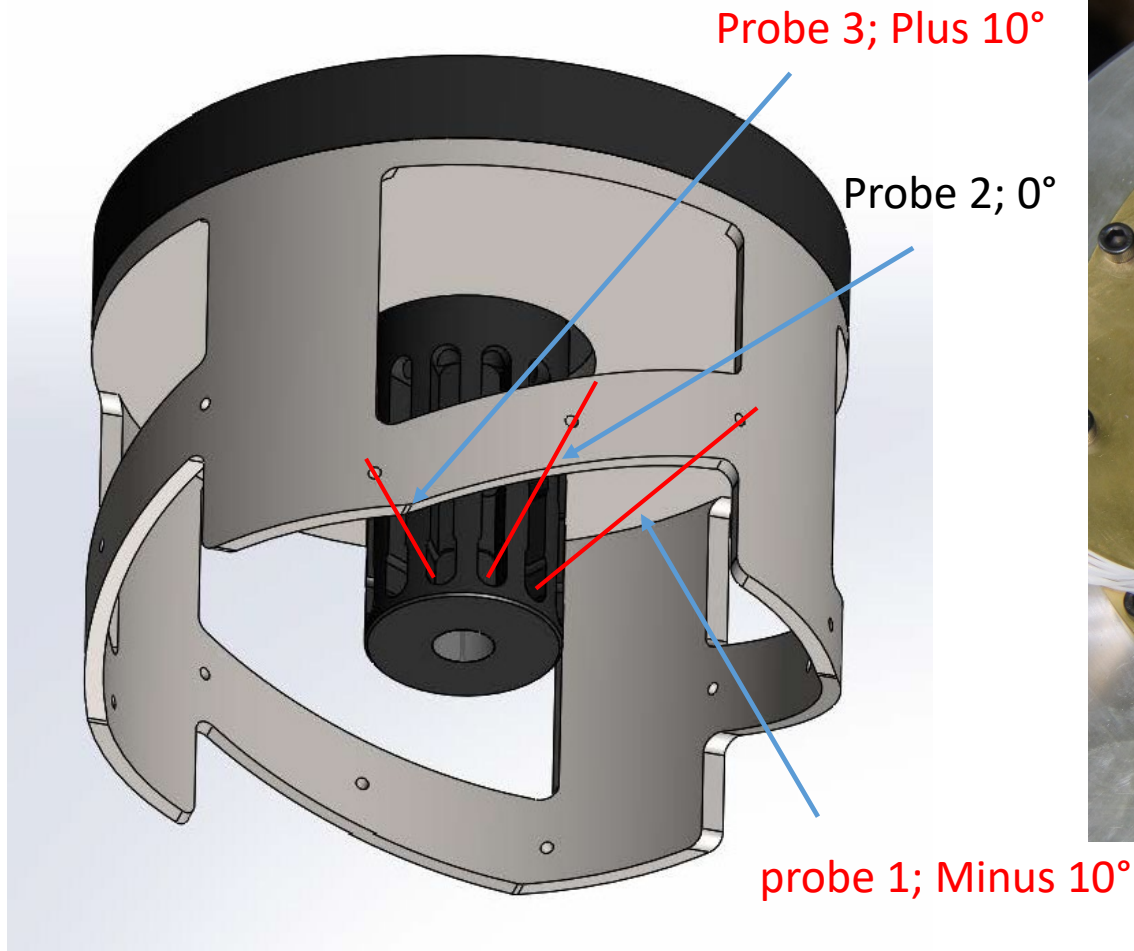


Fibers coming out
of vacuum system



Fibers coming out of CMU

Photo and alignment fixture drawing demonstrate that probes 1, 4, 7, 10 (minus 10° probes) look toward outer glide plane.

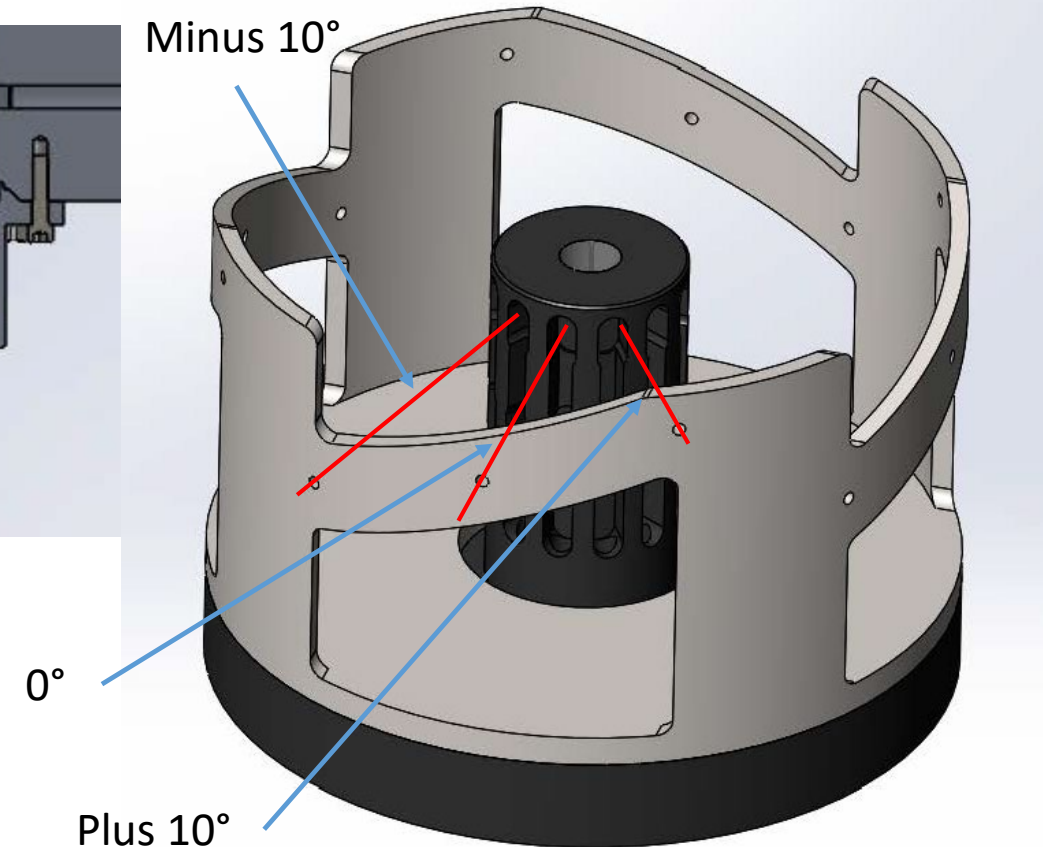
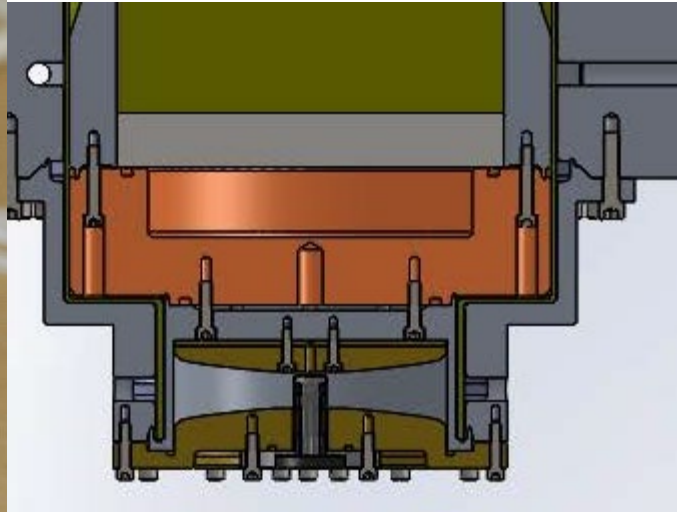


Fibers coming out of CMU

PDV alignment fixture

+10° probes angle toward inner Glide plane
- 10° probes angle toward outer Glide plane

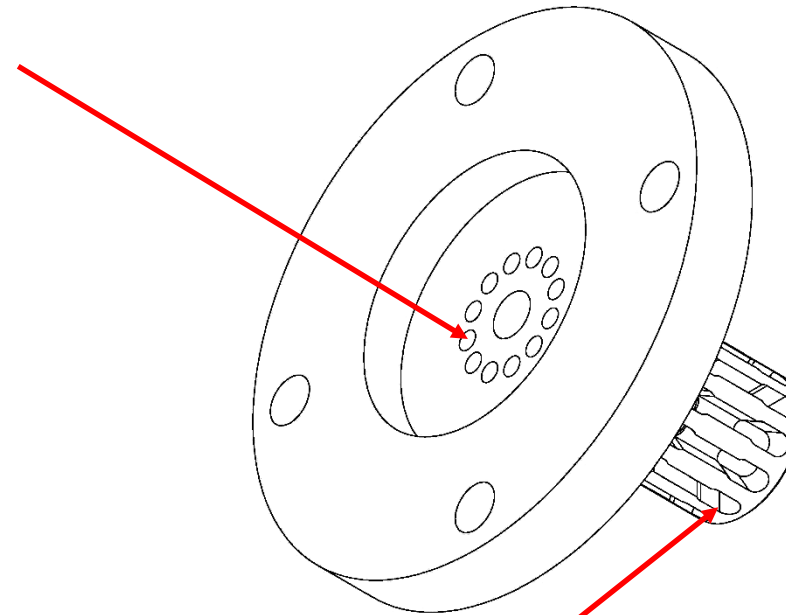
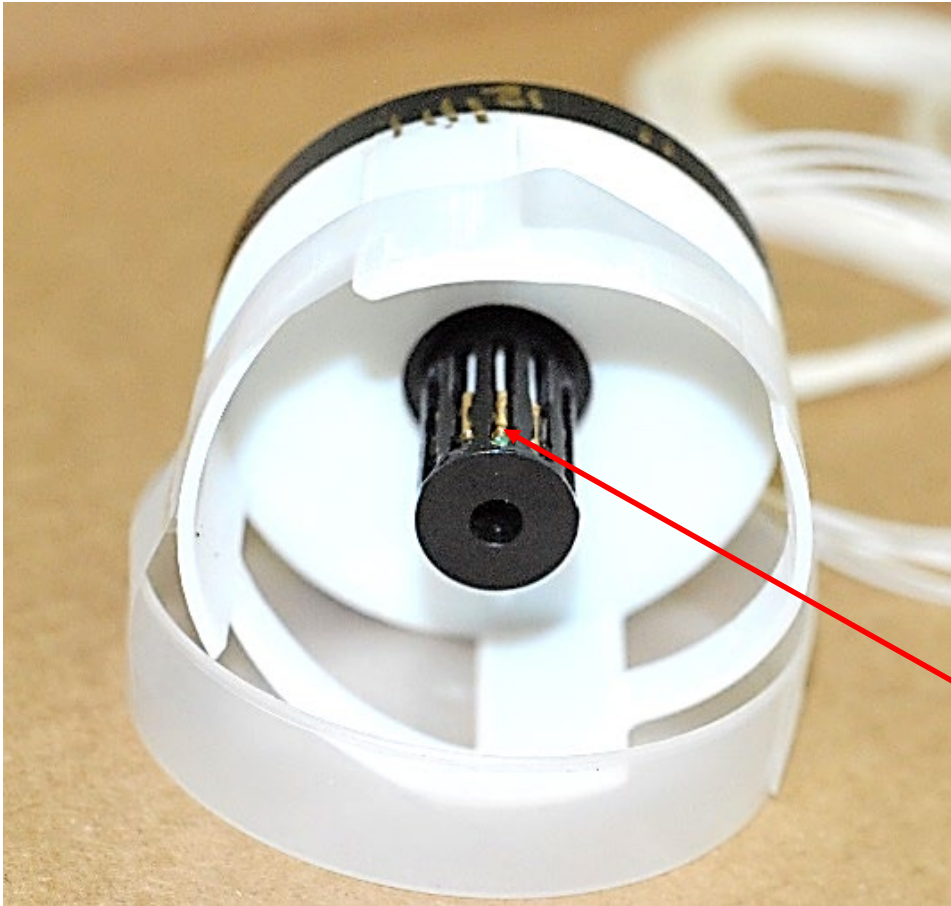
Probe alignments were checked by verifying that PDV LASER light would pass through holes in an alignment fixture.



CMU contains 12 PDV probes

- * Two are recorded in downshifted mode to allow up to 2 cm/ μ s to be recorded
- * Four will observe inward radial motion
- * Four will look at angles above and below normal by 10°

PDV probes were located inside holes in CMU wall.

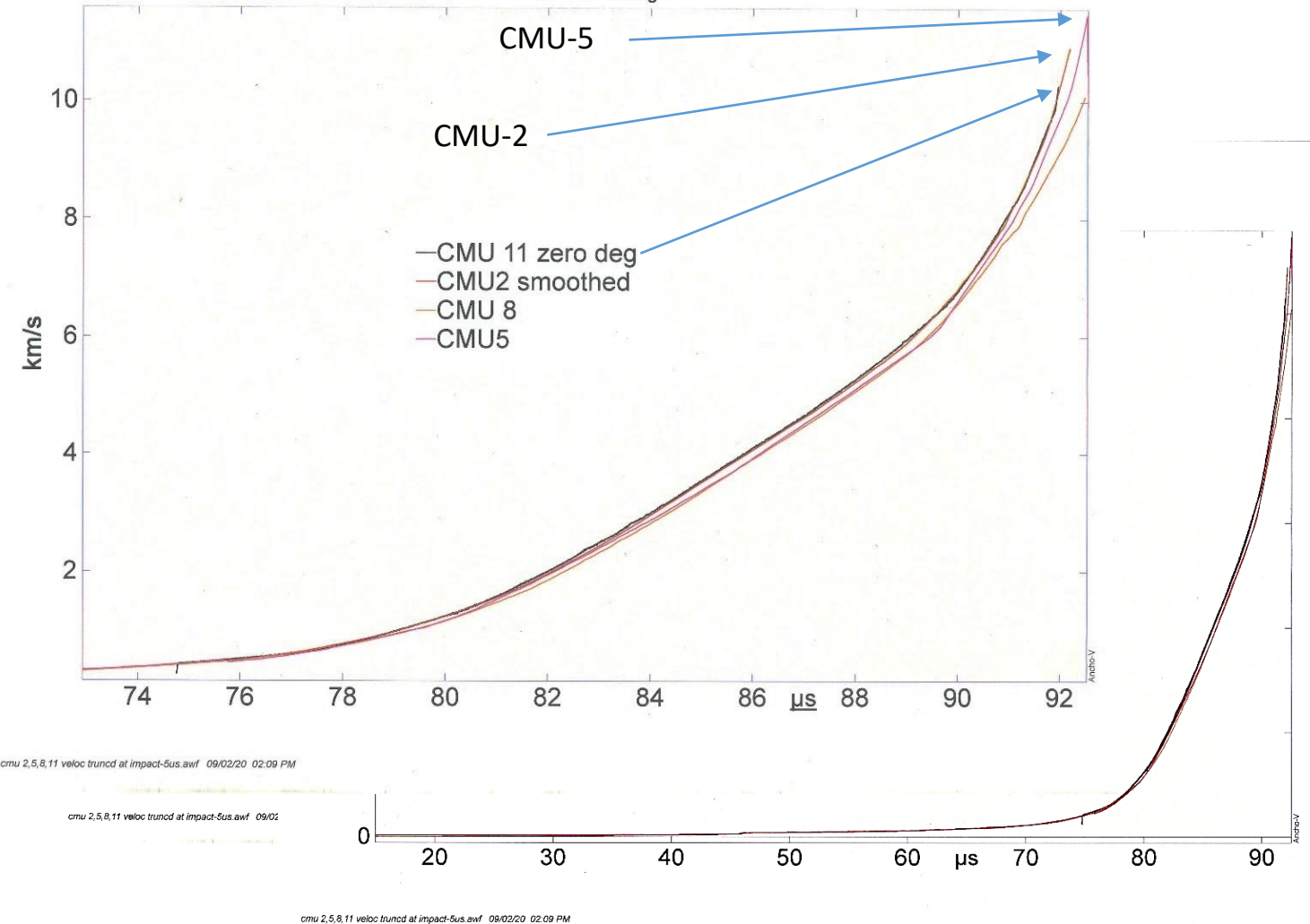


Individual signals

The following show the CMU PDV signals individually and in groups of four viewing at the same angle. They have been synchronized with peak current on Roxane calculation 170509 as will be described below.

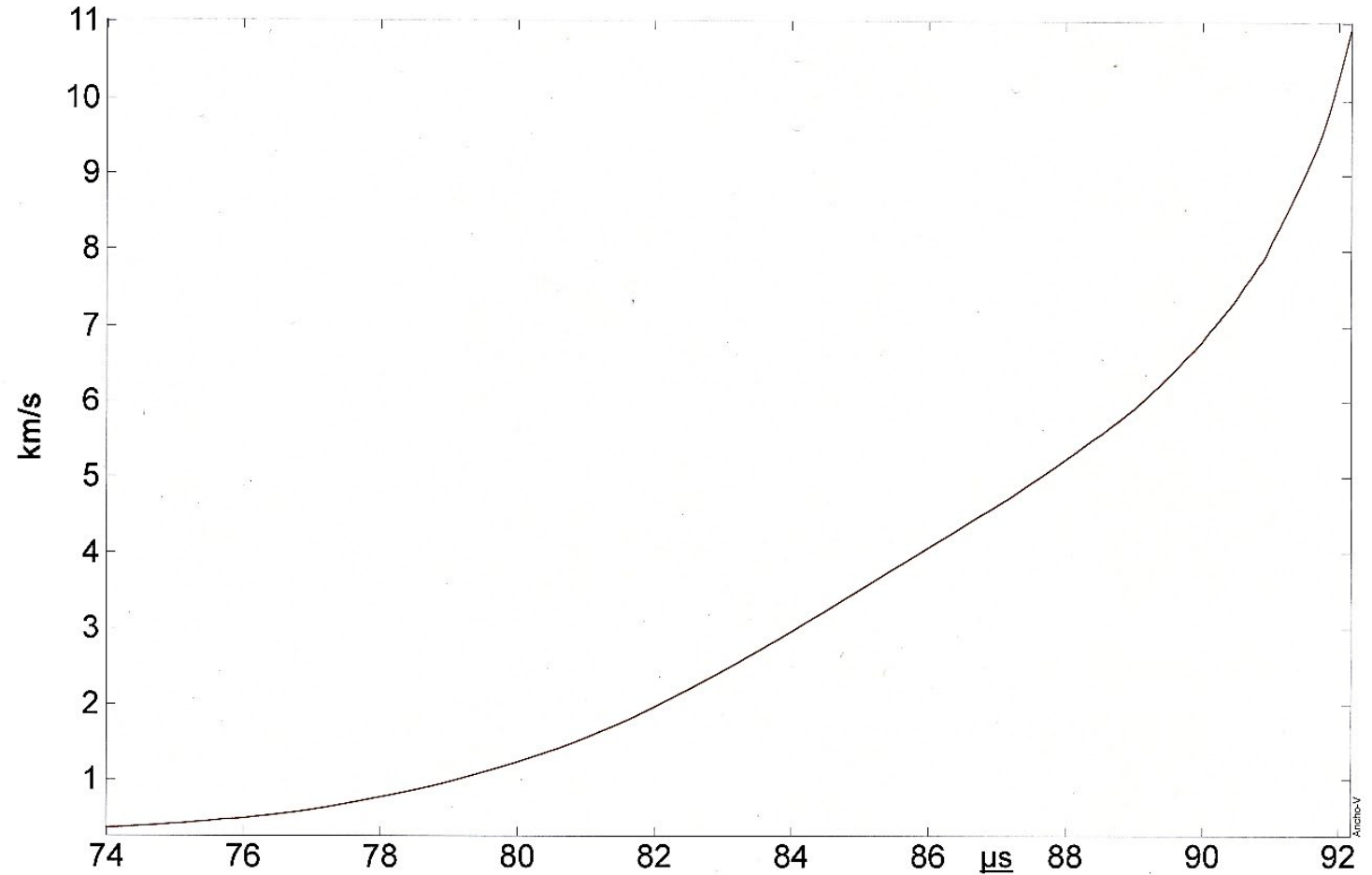
All 0° probe velocity plots synchronized with Roxane peak current at 83.3 μs

- Lower right is plot from current start and upper left is from just before 74 μs until after all probes have ceased functioning.
- All probes exceed 1 cm/ μs .
- Individual plots follow



0° probe CMU 2

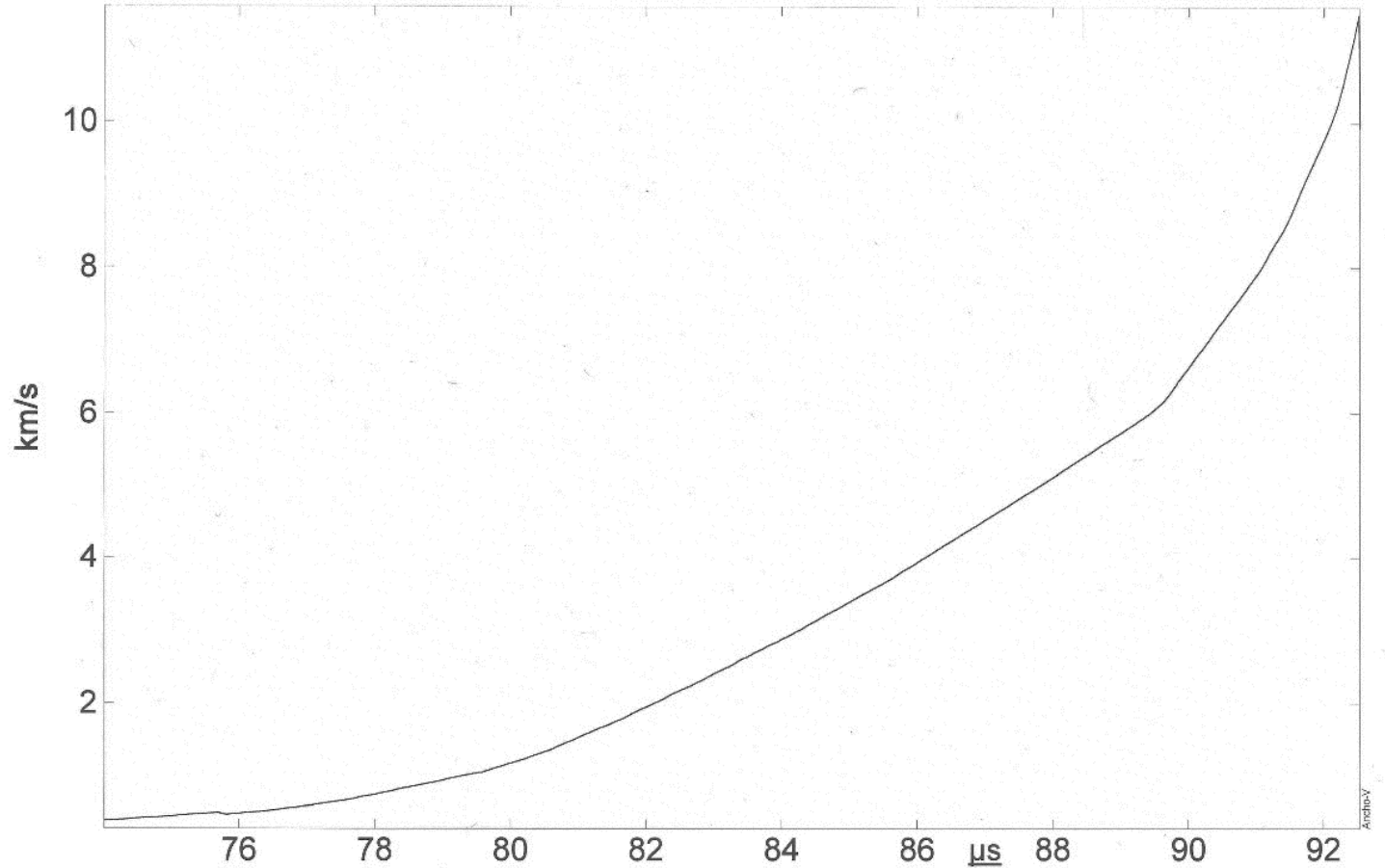
- Peak velocity is 1.09 cm/ μ s @ 92.18 μ s sync'd with Roxane
- Peak current is at 83.3 μ s.



09/02/20 03:09 PM

0° probe CMU 5

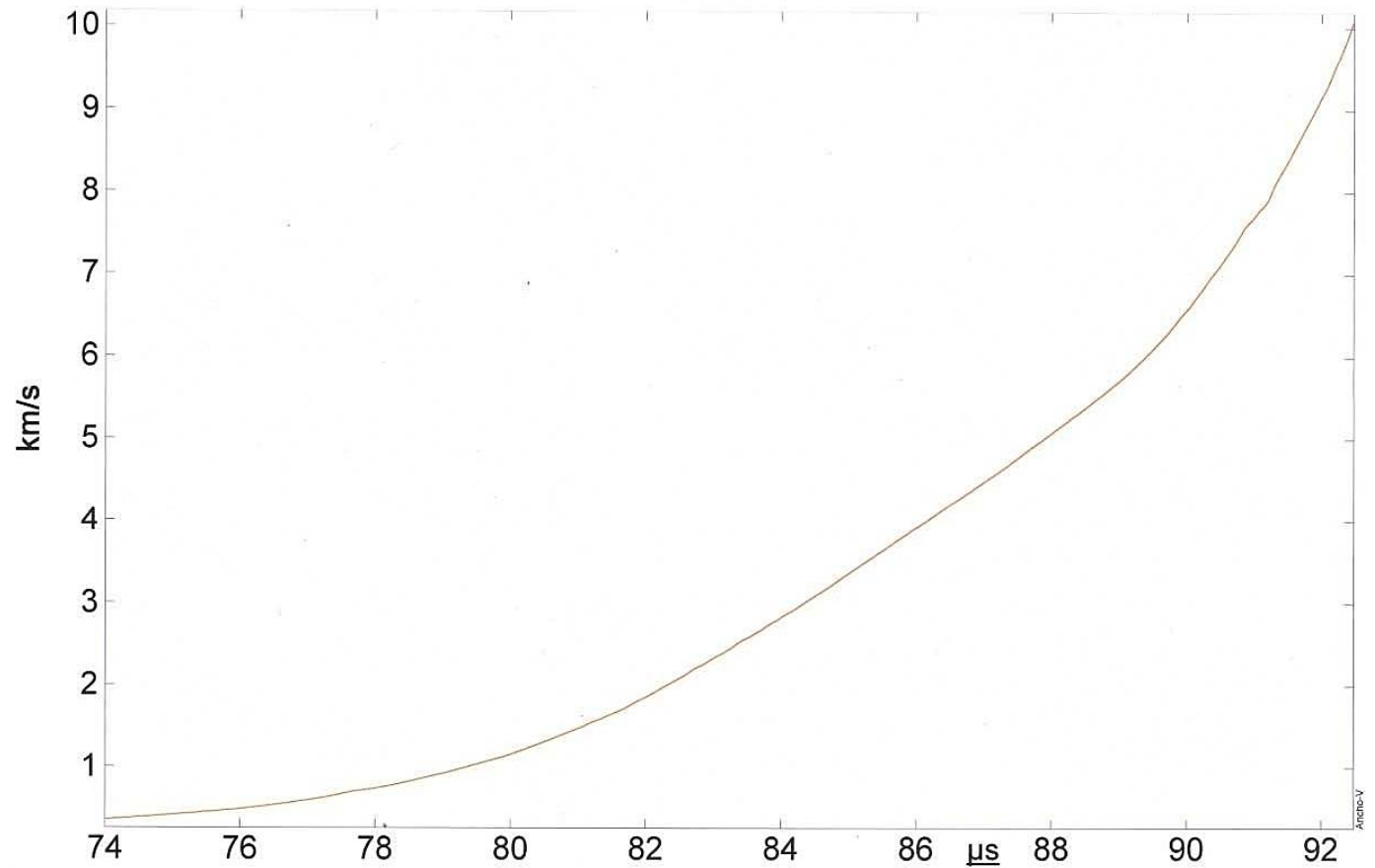
- Peak velocity is 1.14 cm/ μ s @ 92.52 @ μ s sync'd with Roxane
- Peak current is at 83.3 μ s.



09/02/20 03:09 PM

0° probe CMU 8

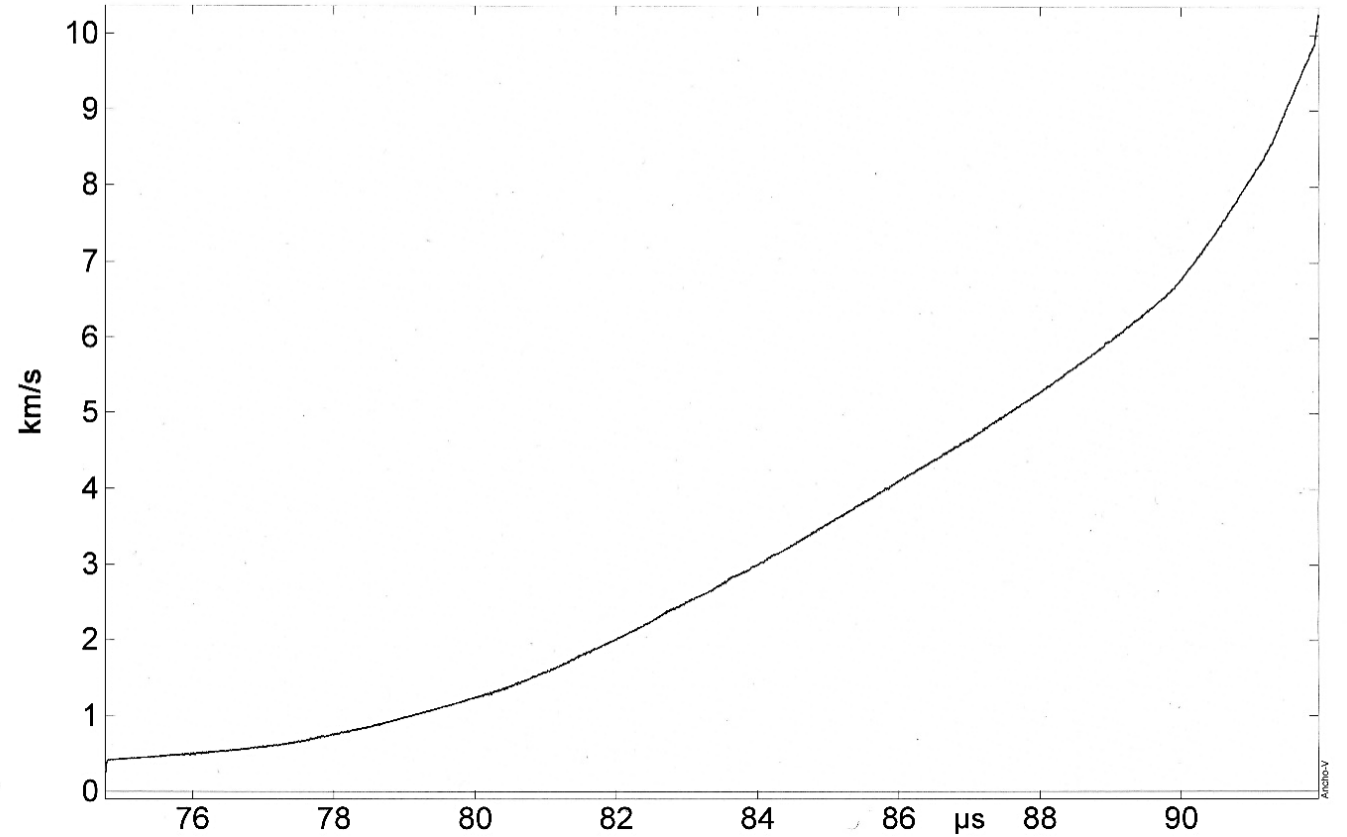
- Peak velocity is 1.01 cm/ μ s@ 92.48 μ s sync'd with Roxane
- Peak current is at 83.3 μ s.



09/02/20 03:09 PM

0° probe CMU 11

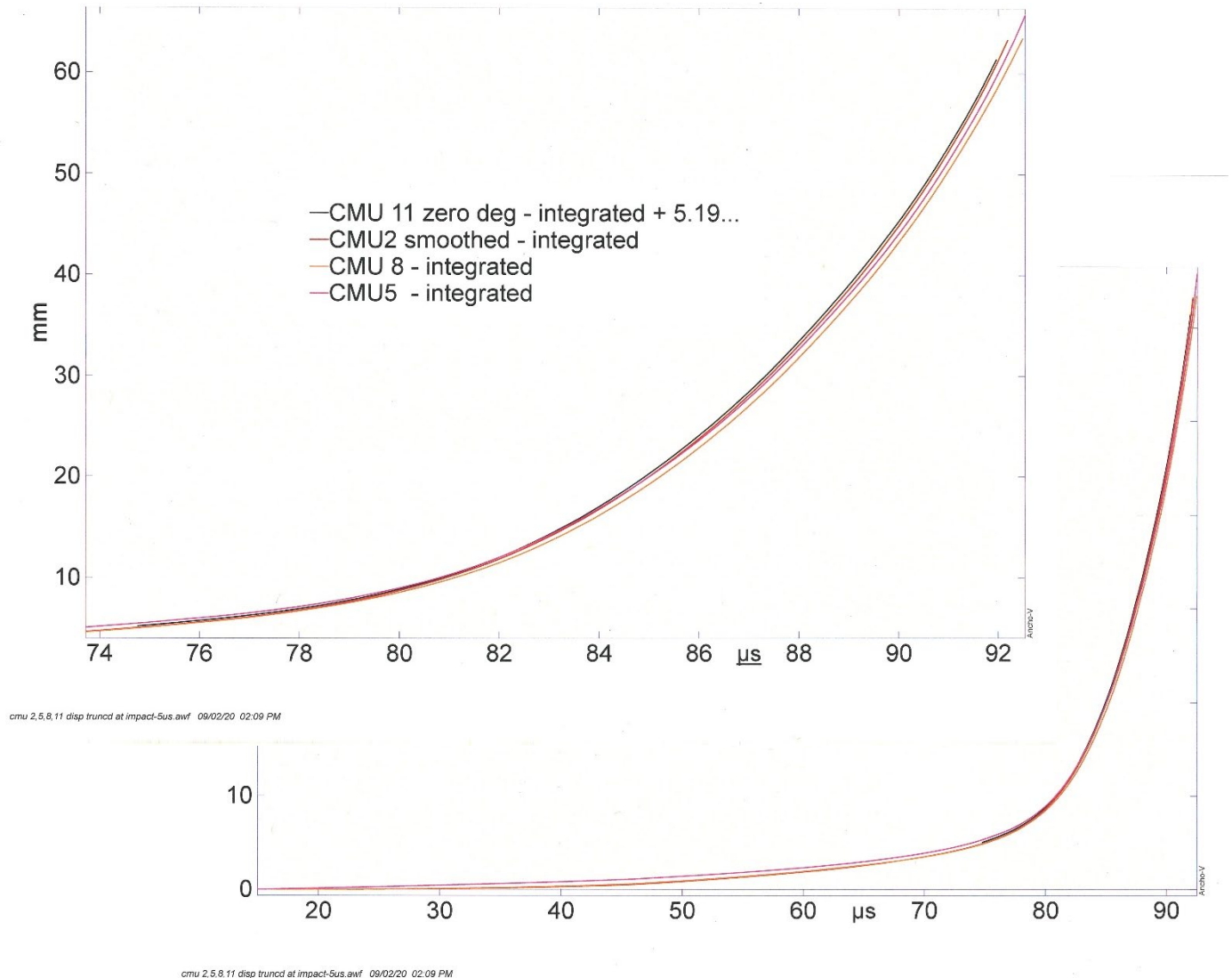
- Peak velocity is 1.03 cm/ μ s @ 91.95 μ s sync'd with Roxane
- Peak current is at 83.3 μ s.



cmu 2,5,8,11 veloc truncated at impact-5us.awf 09/02/20 03:09 PM

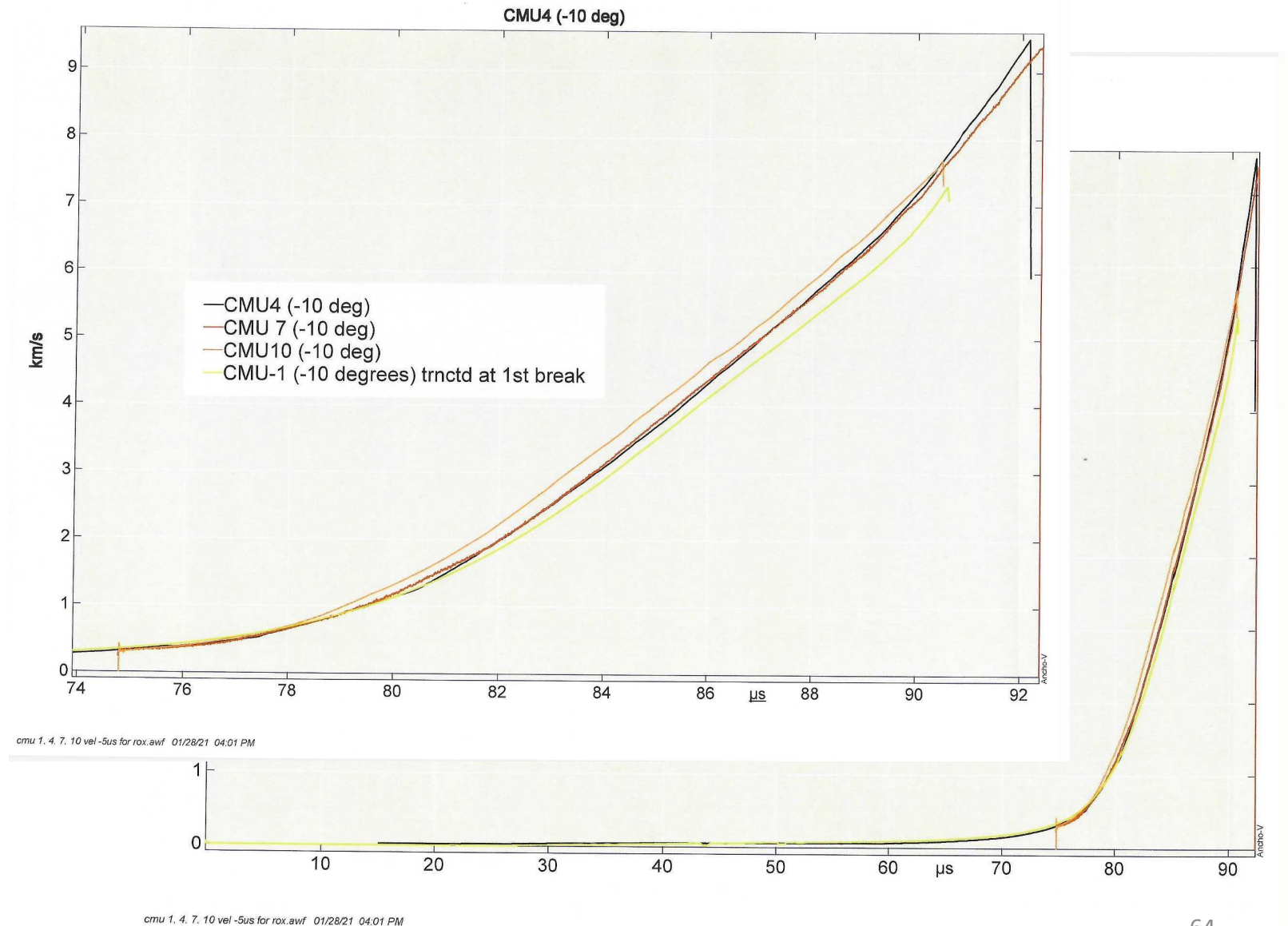
All 0° probe displacement plots synchronized with Roxane peak current at 83.3 μs

- Lower right is plot from current start and upper left is from just before 74 μs until after all probes have ceased functioning.
- Initial inner radius of liner is 75 mm.
- Final liner radius
 - CMU 2; $75 - 63.12 = 11.9 \text{ mm}$ @ 92.16 μs
 - CMU 5; $75 - 65.60 = 9.4 \text{ mm}$ @ 92.52 μs
 - CMU 8; $75 - 63.28 = 11.7 \text{ mm}$ @ 92.46 μs
 - CMU 11; $75 - 61.35 = 13.7 \text{ mm}$ @ 91.95 μs
- Below it will be shown that the final positions can be reconciled with an implosion that is $\sim 2 \text{ mm}$ off-center between probes 5 and 11.



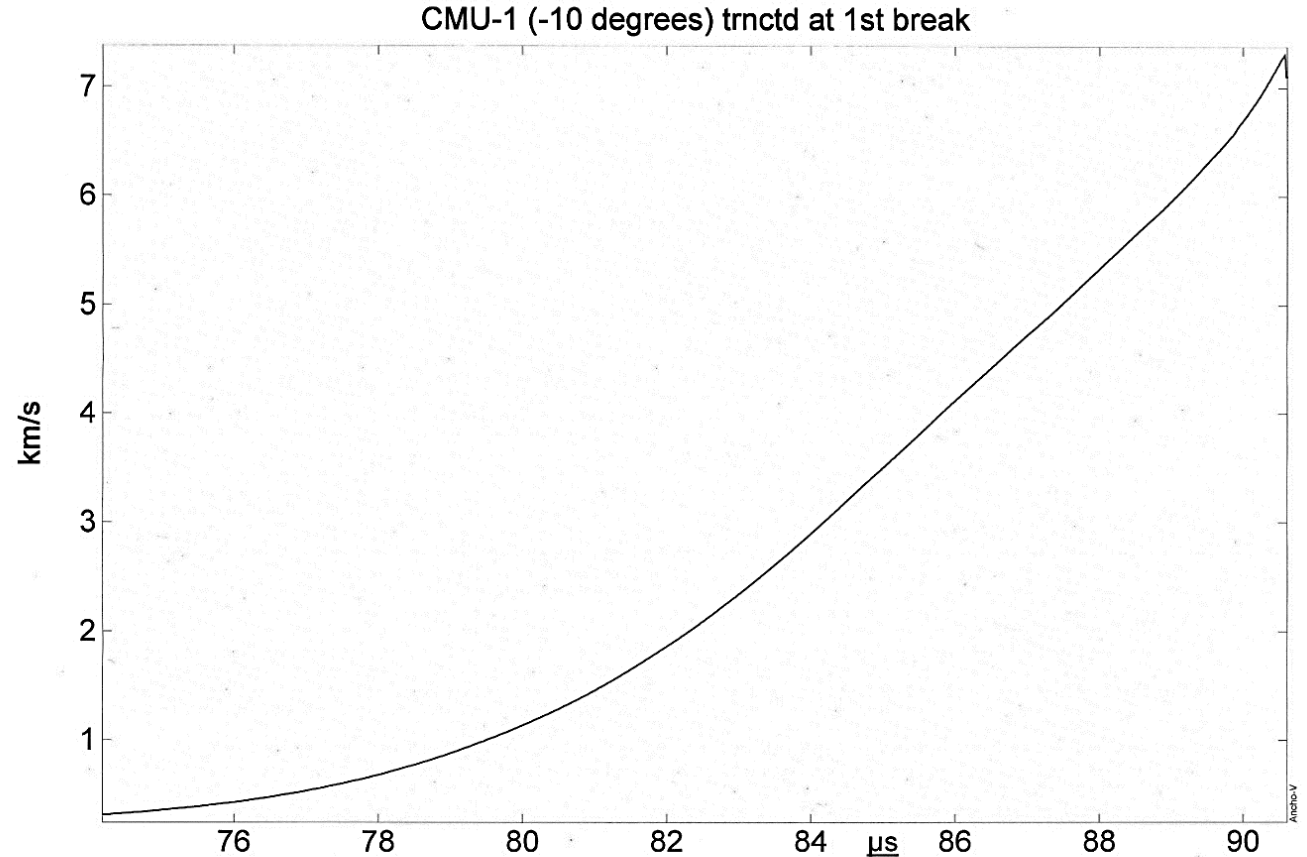
All -10° probe velocity plots synchronized with Roxane peak current at 83.3 μs

- Lower right is plot from current start and upper left is from just before 74 μs until after all probes have ceased functioning.
- Individual plots follow



-10° probe CMU 1 velocity

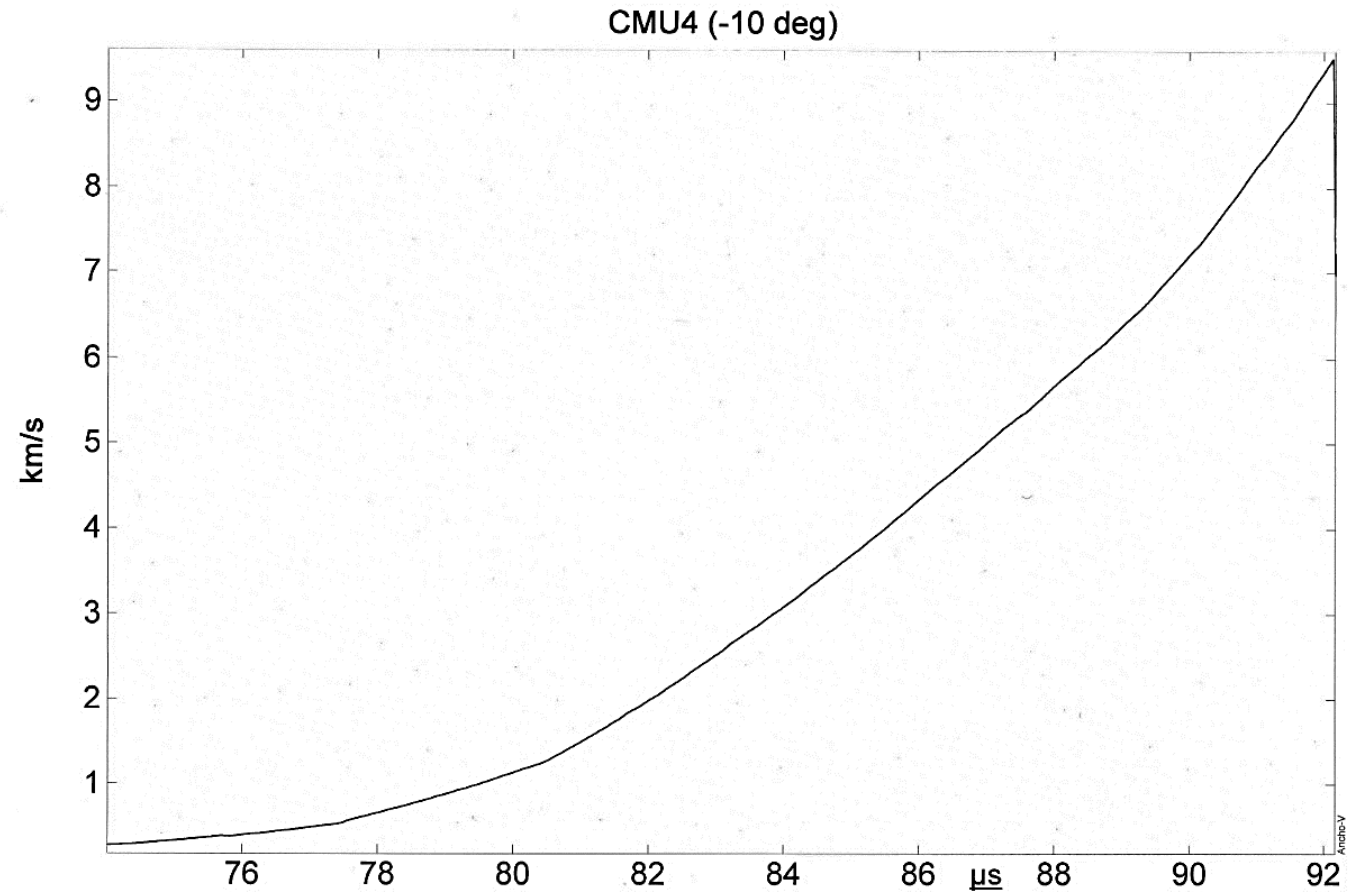
- Peak velocity is 0.73 cm/ μ s @ 90.58 μ s sync'd with Roxane
- Peak current is at 83.3 μ s.



09/02/20 03:09 PM

-10° probe CMU 4 velocity

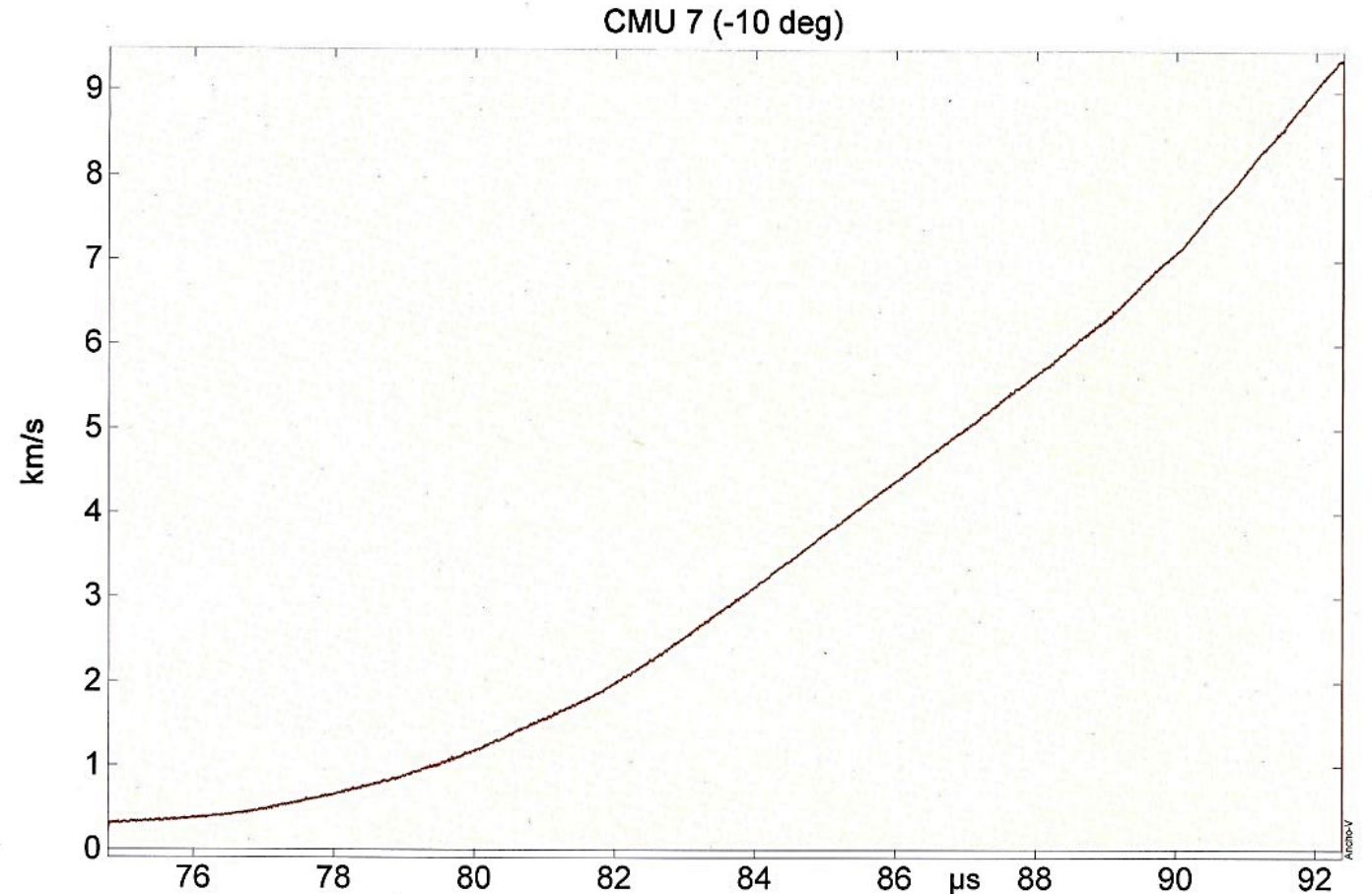
- Peak velocity is 0.95 cm/ μ s @ 92.13 μ s sync'd with Roxane
- Peak current is at 83.3 μ s.



181B2B5FB86D41a7816B1BE4F8EDD46E.cmu 1, 4, 7, 10 velocity -5 ms for rox.awf 09/02/20 03:09 PM

-10° probe CMU 7 velocity

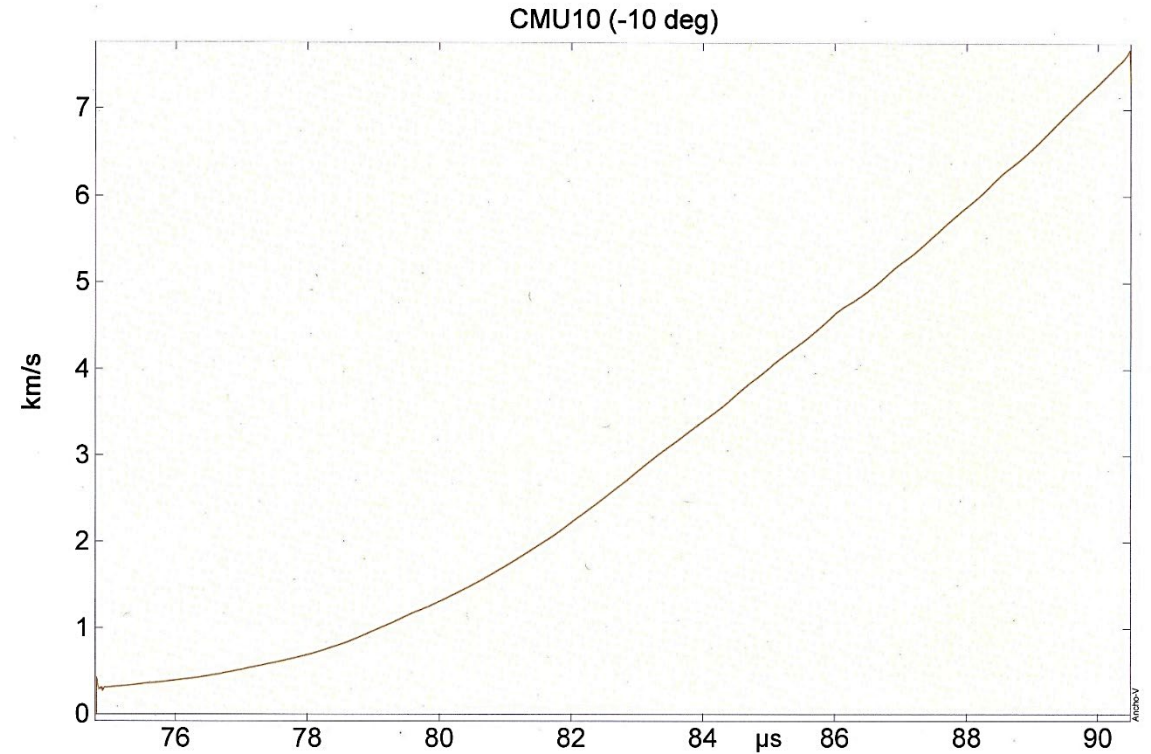
- Peak velocity is 0.94 cm/ μ s @ 92.38 μ s sync'd with Roxane
- Peak current is at 83.3 μ s.



09/02/20 03:09 PM

-10° probe CMU 10 velocity

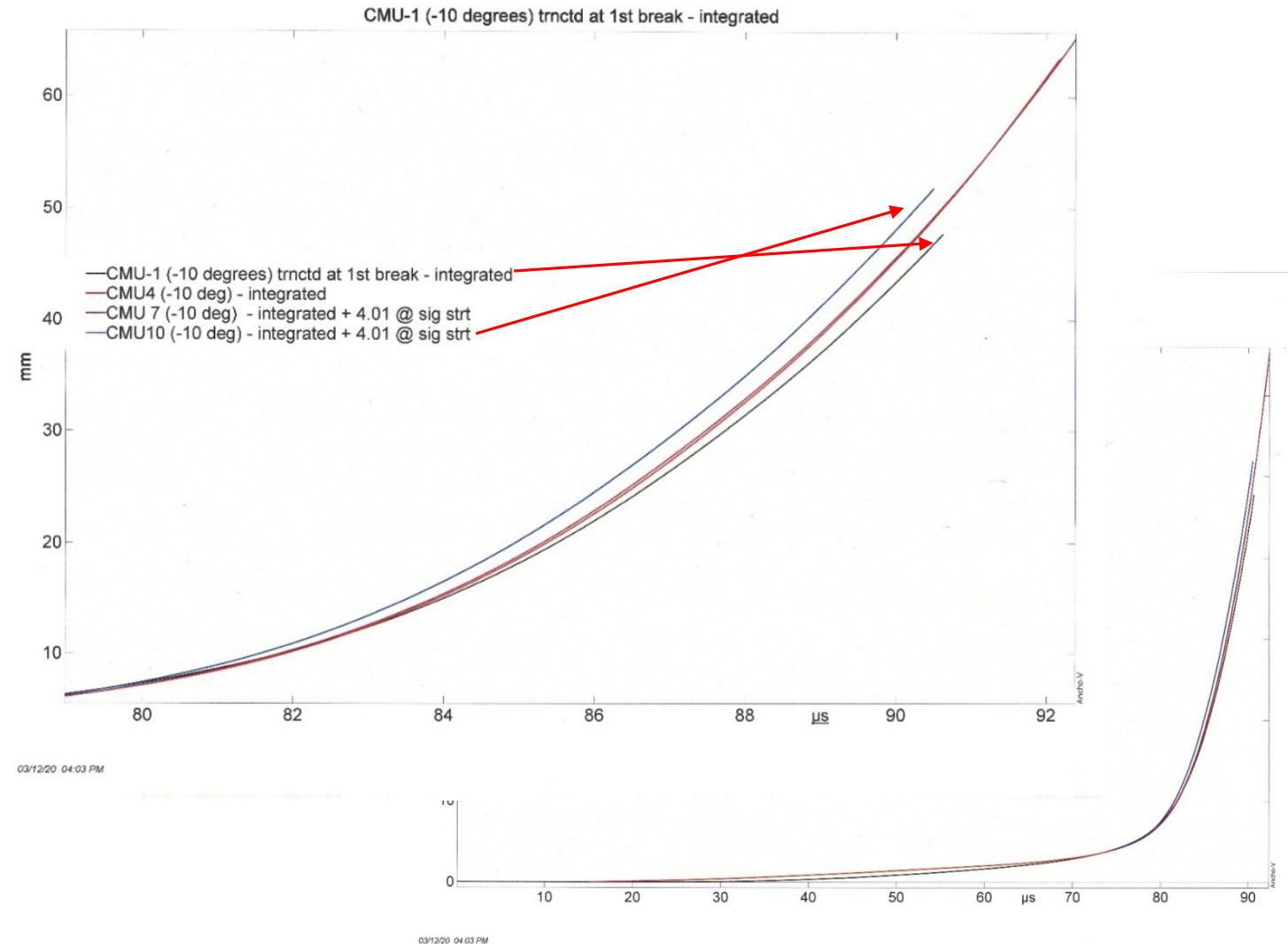
- Peak velocity is 0.77cm/μs @ 90.48 μs sync'd with Roxane
- Peak current is at 83.3 μs.



09/02/20 03:09 PM

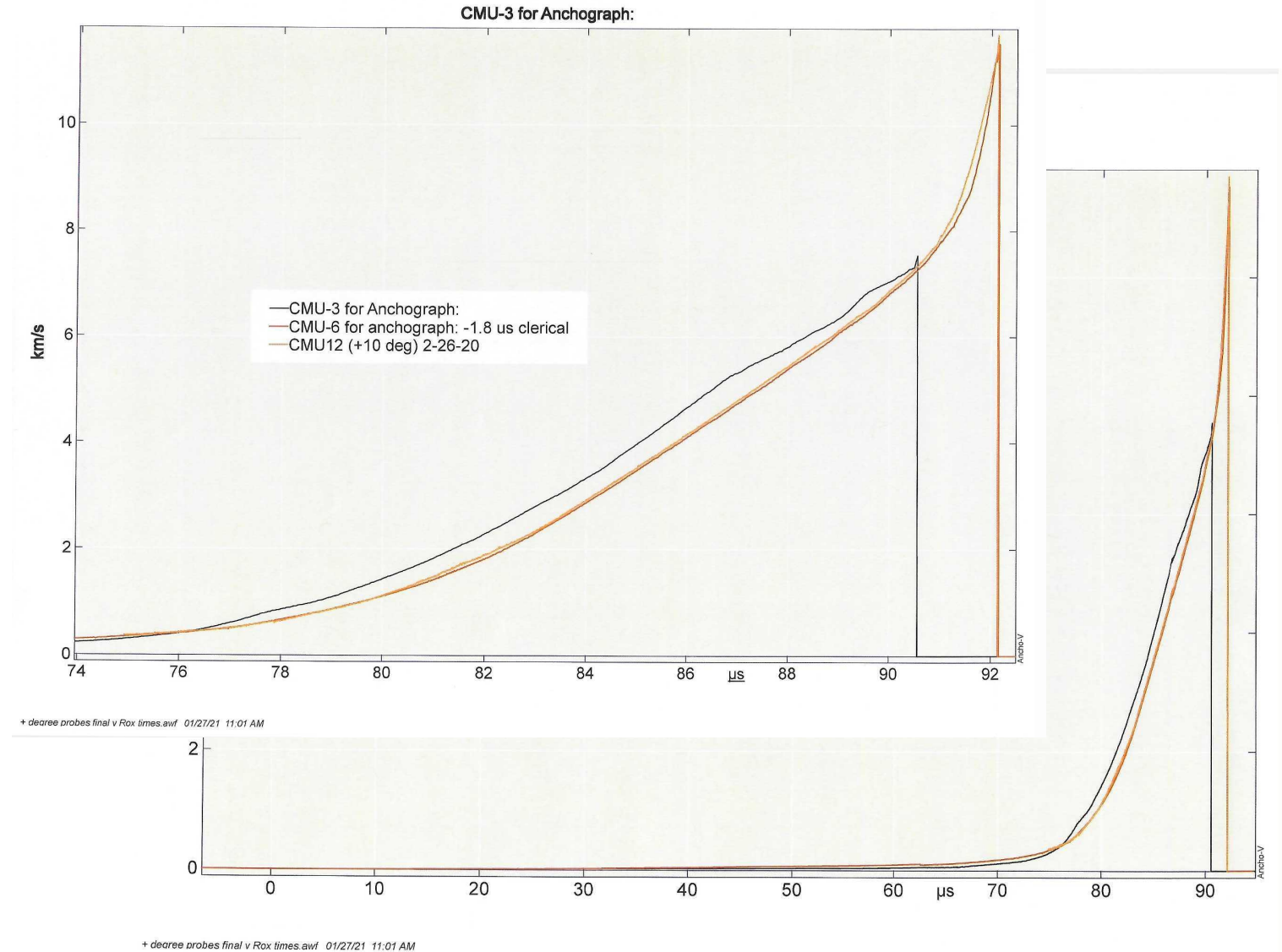
- 10° CMU probes displacement synchronized with Roxane at peak current

- Lower right is plot from current start and upper left is from about 79 μs until after all probes have ceased functioning.
- Initial inner radius of liner is 75 mm.
- Final liner radius
 - CMU 1; $75 - 47.71 = 27.29 \text{ mm}$ @ $90.62 \mu\text{s}$
 - CMU 4; $75 - 63.54 = 11.46$ @ $92.18 \mu\text{s}$
 - CMU 7; $75 - 65.26 = 9.74$ @ $92.39 \mu\text{s}$
 - CMU 10; $75 - 51.83 = 23.17$ @ $90.49 \mu\text{s}$
- Assume the implosion has a center that is half way (8.8mm) between 1 and 7. Likewise 5.9 mm between 4 and 10:
- then Probe 1 is $75 - 63.47 = 18.5 \text{ mm}$ and probe 7 is $75 - 56.4 = 18.5 \text{ mm}$ from center of that circle.
- Likewise, probe 4 is 17.3 mm and probe 10 is 17.3.
- As will be discussed below, these probes are very sensitive to glide plane interactions.



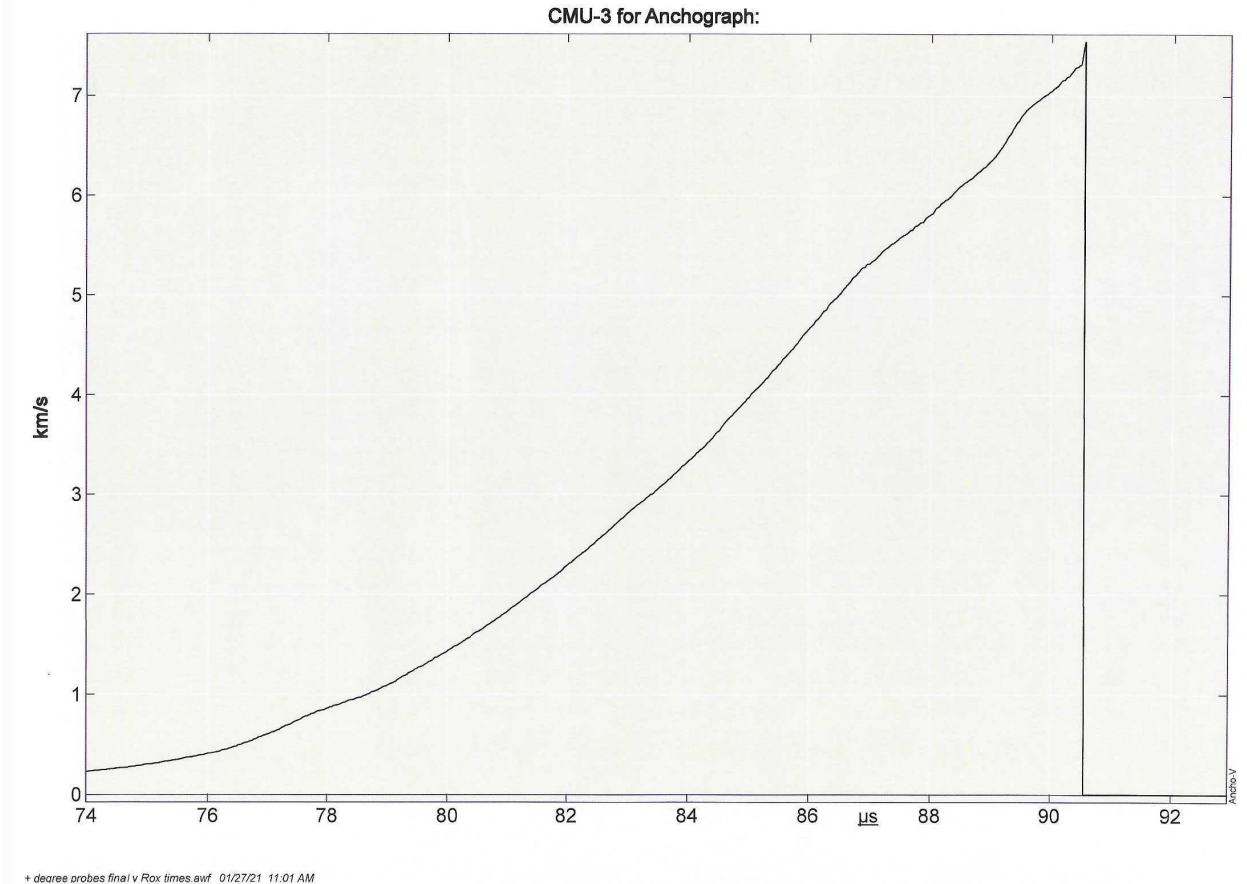
All +10° velocity plots synchronized with Roxane at peak current

- A discussion of the differences follows.



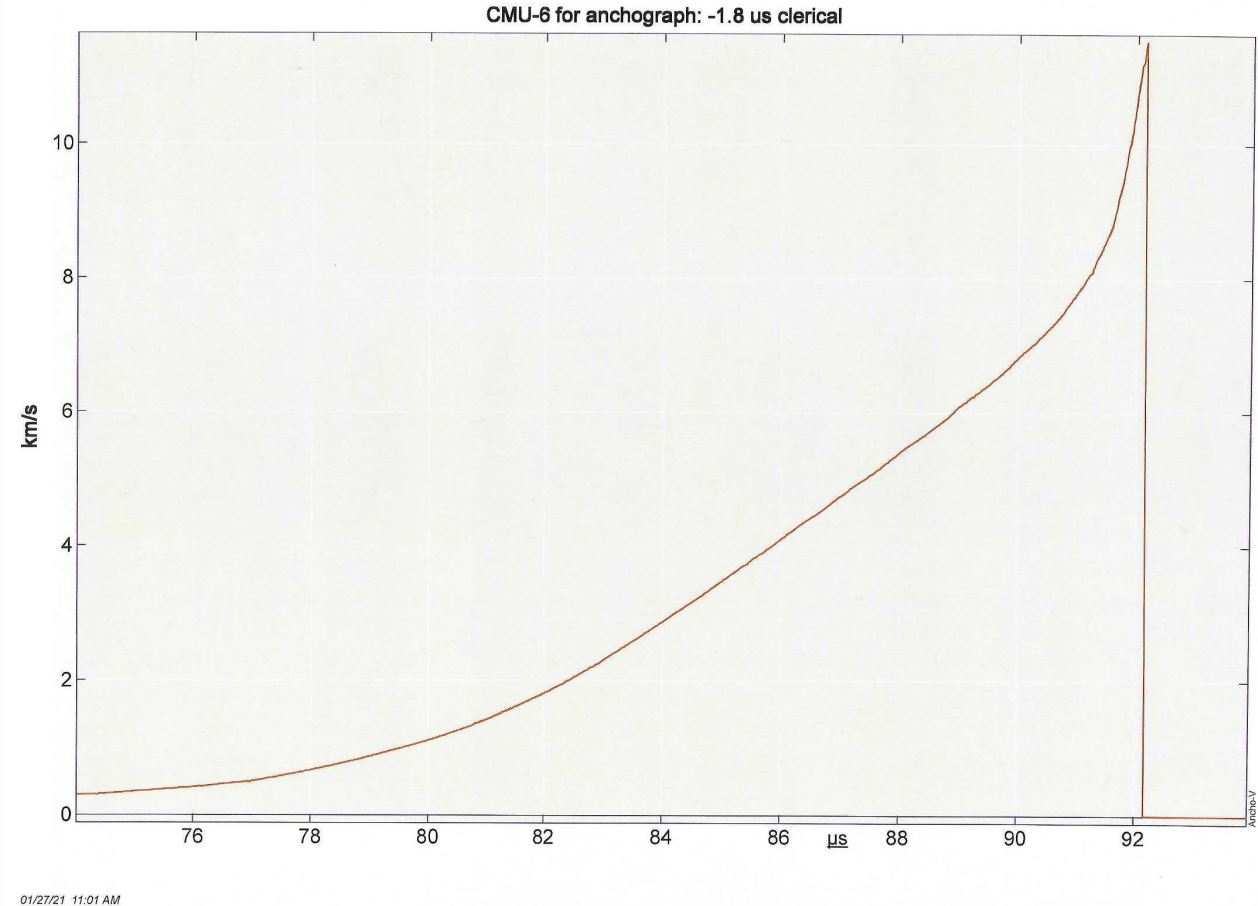
+10° probe CMU 3 velocity

- Peak velocity is 0.76cm/ μ s @ 90.5 μ s sync'd with Roxane.
- This probe showed a loss of signal at this time, then continued to give velocity data for another ~ 0.5 μ s. Since the signal was suspect after the initial signal loss, it is truncated at the time of the initial loss.
- Peak current is at 83.3 μ s.



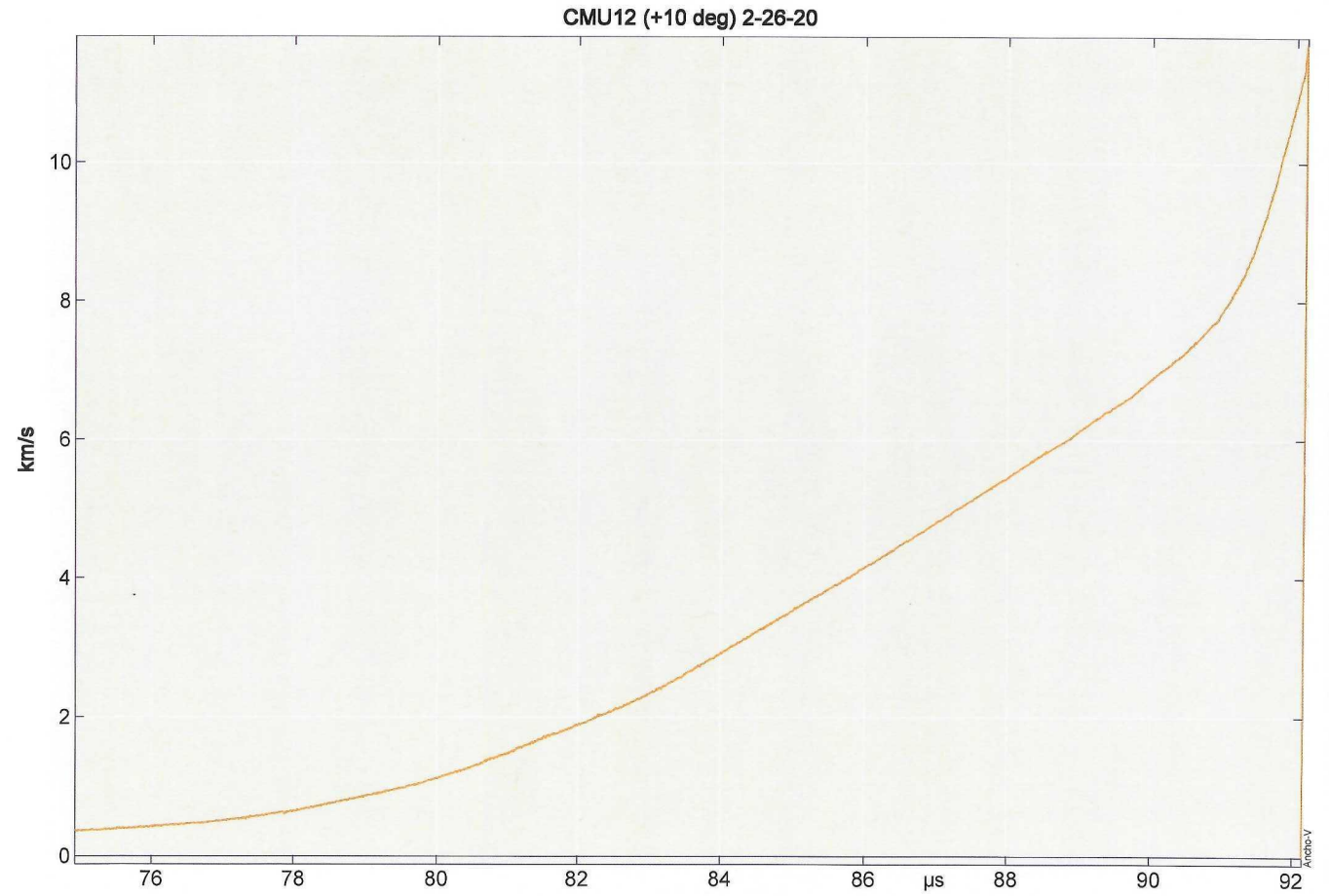
+10° probe CMU 6 velocity

- Peak velocity is 1.15 cm/ μ s @ 92.1 μ s sync'd with Roxane
- Peak current is at 83.3 μ s.



+10° probe CMU 12 velocity

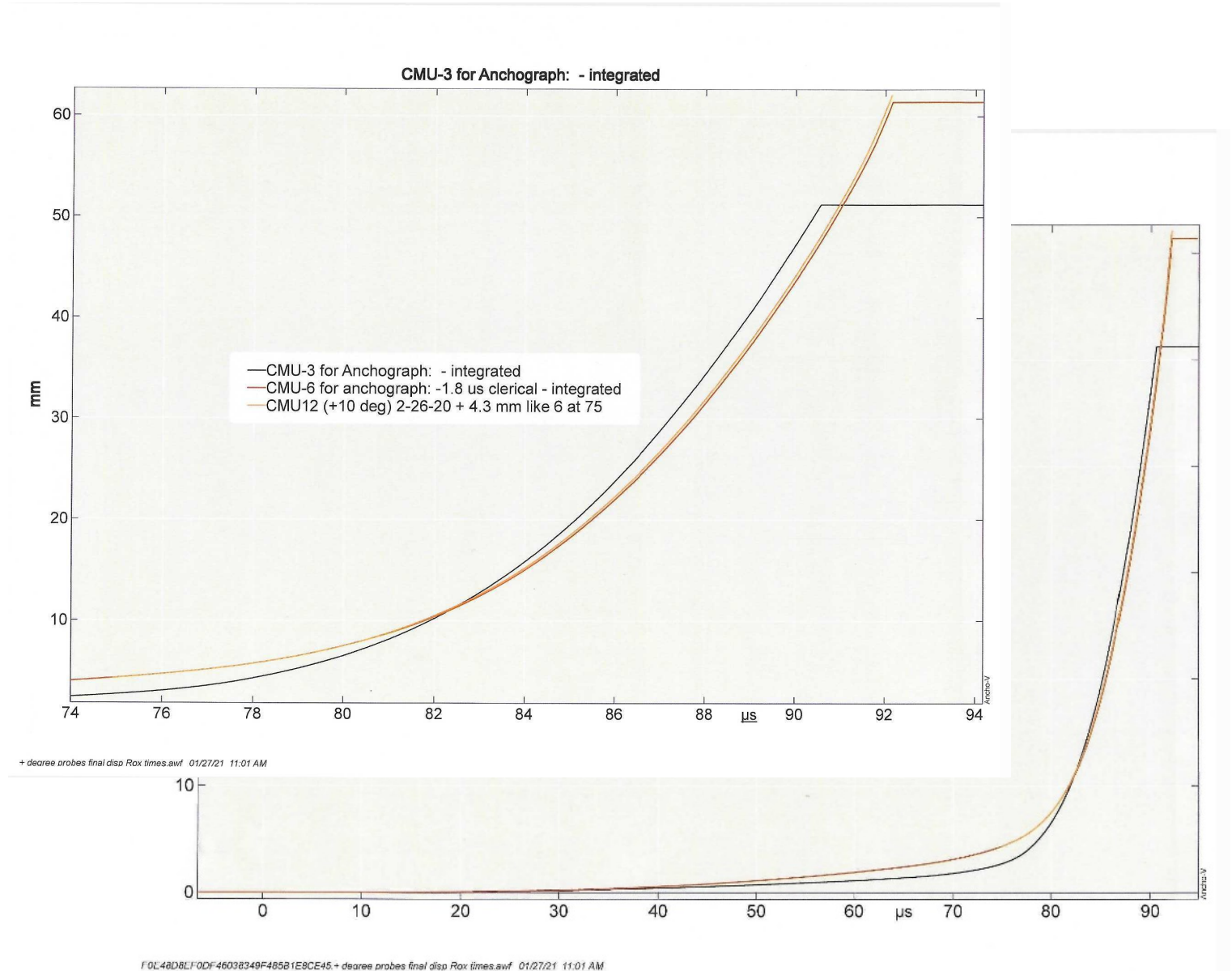
- Peak velocity is 1.17cm/ μ s @ 92.14 μ s sync'd with Roxane
- Peak current is at 83.3 μ s.



01/27/21 11:01 AM

+ 10° CMU probes displacement synchronized with Roxane at peak current

A discussion of the differences follows.



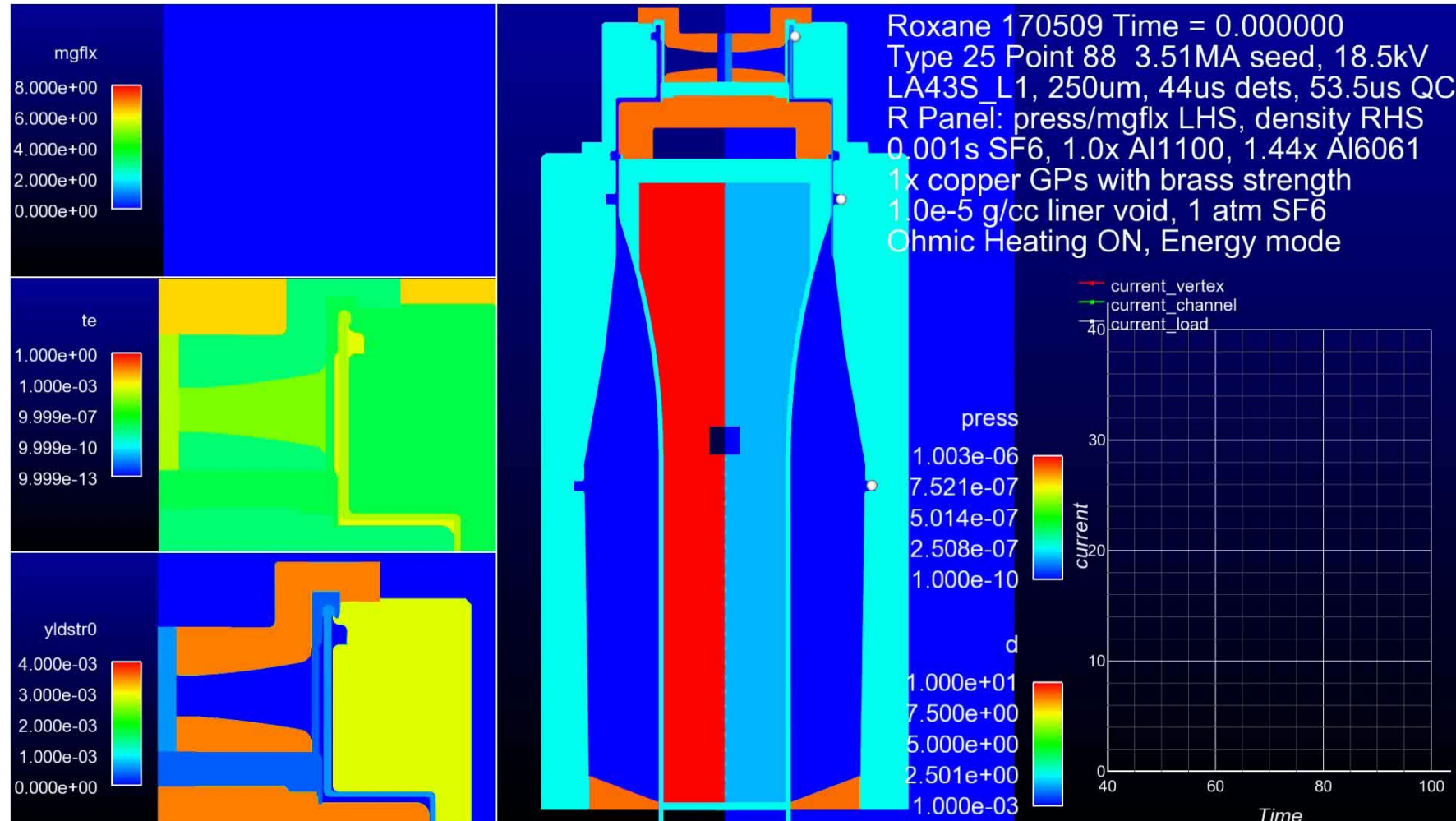
A Roxane calculation, with
movie given below, has been
synchronized with
experiment and used
throughout CMU analysis

Synchronizing LA-R43S6 L1 data and calculation170509

- In the following analysis, a careful comparison is made to a Roxane calculation performed by Bob Watt designated 170506 (that is May 6 of 2017). The following describes how data are synchronized with this calculation.
- 170509 has an external circuit with the best understanding of the point 88 capacitor bank, and current from the bank starts at zero in the calculation.
- 170509 detonates charges on axis at $44\text{ }\mu\text{s}$, which produces first motion between dumps at 52.91 and $53.91\text{ }\mu\text{s}$. In the legend it states 53.5 QC (quarter cycle) so we assume that first motion is at that time.
- Peak current in 170509 is at the data dump at $83.3\text{ }\mu\text{s}$.
- With scope data shifted to have zero at current start on experiment, first motion is at 52.01 and peak current is 83.40
- During the analysis we compared syncing PDV probes with first motion of the Ranchero Armature to syncing the probes with peak current. Synchronizing with peak current gives a considerably better comparison and that analysis follows.

This is run 170509. It is the best post shot calculation made shortly after the shot.

The movie shows an end-to-end calculation of the entire experiment, with an external circuit that simulates the initial current from the firing point 88 capacitor bank as accurately as possible.



Liner positions determined at dump times of above Roxane calculation along lines of sight for the indicated PDV probes.

These are dump times in a Roxane movie of 170509.										
		Roxane dump time (μ s)	79.86	86.09	88.49	89.48	90.49	91.53	92.53	
Probe number	Probe angle (degree)		radial position (mm)	radial position (mm)	radial position (mm)	radial position (mm)	radial position (mm)	radial position (mm)	radial position (mm)	
CMU-1	-10		66.7	52.2	40.5	34.7	28.3	20.9	12.7	
CMU-4	-10		66.7	52.2	40.5	34.7	28.3	20.9	12.7	
CMU-7	-10		66.7	52.2	40.5	34.7	28.3	20.9	12.7	
CMU-10	-10		66.7	52.2	40.5	34.7	28.3	20.9	12.7	
CMU-2	0		66.3	51.2	40.5	35	29.1	21.6	13.4	
CMU-5	0		66.3	51.2	40.5	35	29.1	21.6	13.4	
CMU_8	0		66.3	51.2	40.5	35	29.1	21.6	13.4	
CMU-11	0		66.3	51.2	40.5	35	29.1	21.6	13.4	
CMU-3	10		66.7	52.2	40.5	34.7	28.3	20.9	12.7	
CMU-6	10		66.7	52.2	40.5	34.7	28.3	20.9	12.7	
CMU-9	10		66.7	52.2	40.5	34.7	28.3	20.9	12.7	
CMU-12	10		66.7	52.2	40.5	34.7	28.3	20.9	12.7	

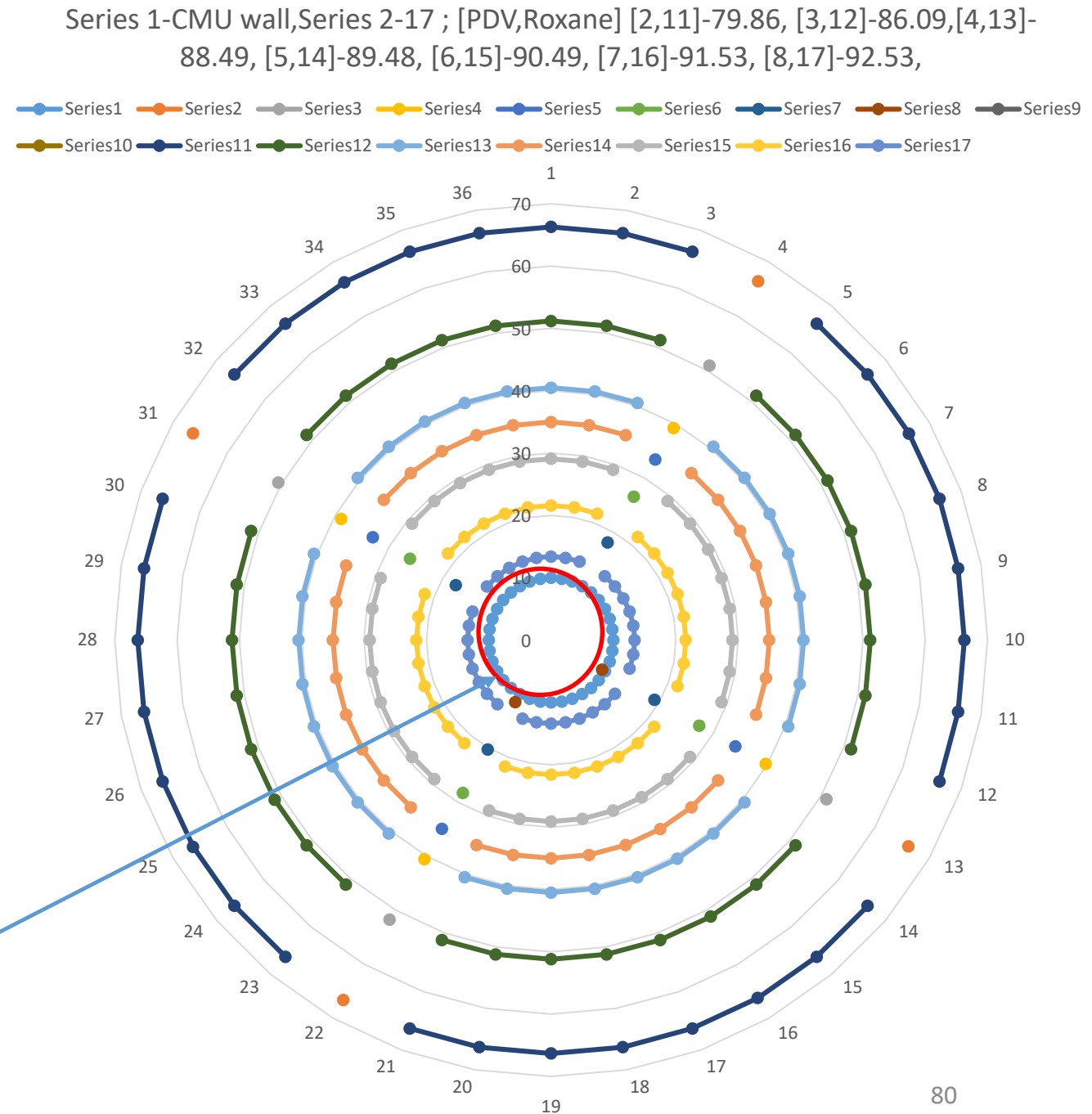
0° probes

- Initial inner radius of liner is 75 mm.
- As shown above, liner radius at signal loss
 - CMU 2; $75 - 63.12 = 11.9$ mm @ $92.16 \mu\text{s}$
 - CMU 5; $75 - 65.60 = 9.4$ mm @ $92.52 \mu\text{s}$
 - CMU 8; $75 - 63.28 = 11.7$ mm @ $92.46 \mu\text{s}$
 - CMU 11; $75 - 61.35 = 13.7$ mm @ $91.95 \mu\text{s}$
- Assume the implosion has a center that is half way (2.15mm) between 5 and 11. Likewise 0.1 mm between 8 and 2:
 - then Probe 5 is $63.47 = 11.5$ mm and probe 11 is $75 - 63.48 = 11.5$ mm from center of that circle.
 - Likewise, probe 2 is 11.8 mm and probe 8 is 11.8.
 - This assumption assumes all probes died ~the same distance from the CMU; ~1.5 or ~1.8 mm. Assuming $10 \text{ mm}/\mu\text{s}$, arrival at the skewed circle has a maximum excursion of 147 ns (between opposing probes 5 and 11) and an oblateness of 0.3 mm represents 30 ns. Similar conclusions can also be reached by drawing a circle through the points centered as noted below.

0° CMU probes synchronized with Roxane at peak current

Zero degree probes at Roxane times with 5 μ s subtracted from scopes to synchronize with Roxane peak I. The data show the liner has moved further than in the calculation.

- Series 1 locates the wall of the CMU
- Probes 2, 5, 8, 11 correspond to positions 4, 13, 22, and 31
- Compare series:
 - 2,11 [79.86 μ s]; 3,12 [86.09 μ s]; 4,13 [88.49 μ s]
 - 5,14[89.48 μ s]; 6,15[90.49 μ s]; 7,16[91.53 μ s]
 - 8,17[92.52 μ s]
 - Series 9 and 10 have no points
- In this synchronization, data points have gotten ahead of Roxane points. In addition two of the probes have failed prior to series 8. Those two probes are on the side of the liner that is running ahead, as can be seen in series 7, and those probes have, no doubt, already impacted the CMU. The other two probes are just reaching the CMU at that time.
- From the analysis above, the center of the implosion is displaced ~2mm towards probe 11 (position 31) as given approximately by the red circle.



-10° probes following the analysis above

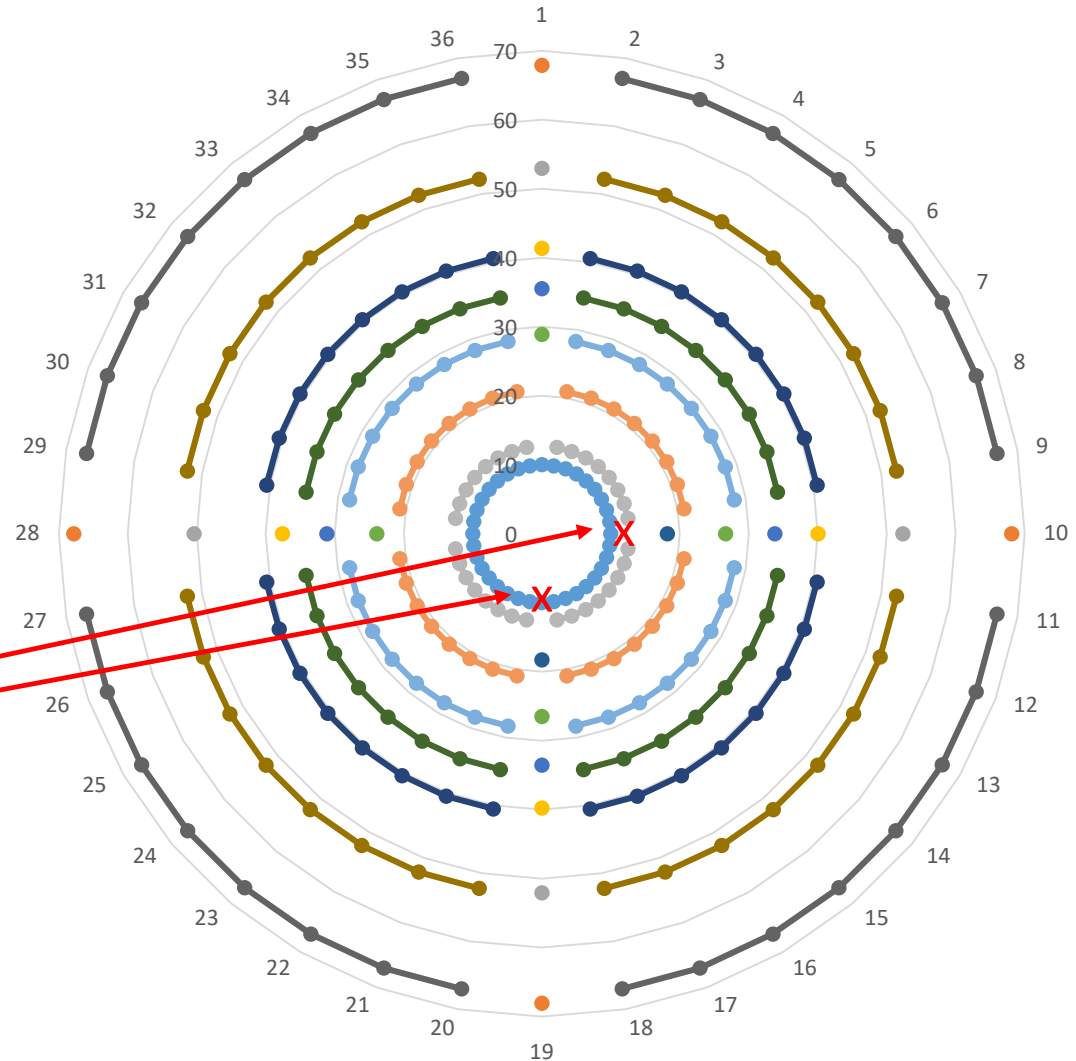
- Initial inner radius of liner is 75 mm.
- Liner radius at signal loss
 - CMU 1; $75 - 47.71 = 27.29$ mm @ $90.62 \mu\text{s}$
 - CMU 4; $75 - 63.54 = 11.46$ @ $92.18 \mu\text{s}$
 - CMU 7; $75 - 65.26 = 9.74$ @ $92.39 \mu\text{s}$
 - CMU 10; $75 - 51.83 = 23.17$ @ $90.49 \mu\text{s}$
- The analysis performed successfully on the zero degree probes is not very useful for the minus 10 degree probes. Following that analysis:
 - Assume the implosion has a center that is half way (8.8mm) between 1 and 7. Likewise 5.9 mm between 4 and 10: then Probe 1 is $75 - 63.47 = 18.5$ mm and probe 7 is $75 - 56.4 = 18.5$ mm from center of that circle. Likewise, probe 4 is 17.3 mm and probe 10 is 17.3. This analysis assumes all probes died ~the same distance from the CMU; ~8.5 or ~7.3 mm.
- As will be seen below following a comparison of the signals to the MHD calculations, the cause of signal loss on these probes is likely the arrival of the glide plane interaction with the signal line of sight. In this case, small variations in probe location would be very critical, and this is the more likely reason for signal termination rather than proximity to the CMU.

- 10° CMU probes (probes angled away from the FCG) synchronized with Roxane at peak current. Displacement corrected by $\cos 10^\circ$

Series 1 CMU wall, Series 2-15 [PDV,Roxane]; [2,9]-79.86, [3,10]-86.09, [4,11]-88.49, [5,12]-89.49, [6,13]-90.49, [7,14]-91.53, [8,15]-92.52

Series1 Series2 Series3 Series4 Series5 Series6 Series7 Series8
Series9 Series10 Series11 Series12 Series13 Series14 Series15

- Probes 1, 4, 7, 10 are positions 1,10, 19, and 28 respectively.
- Series 1 locates the wall of the CMU
- Compare series:
 - 2,9 [79.86 μs]
 - 3,10 [86.09 μs]
 - 4,11 [88.49 μs]
 - 5,12 [89.48 μs]
 - 6,13 [90.49 μs]
 - 7,14 [91.53 μs]
 - 8,15 [92.52 μs]
- None of the probes still had signal at 92.5 (series 15), although **probe 4** lasted until 92.18 and was at **11.46 mm** and **probe 7** lasted until 92.39 and was at **9.74 mm**. As with the 0° probes, the data points are past where the calculations indicates they should be, and below we will show that small errors in probe placement or alignment can have a large impact on the time at which signal is lost due to the glide plane interaction deflecting the return signals.



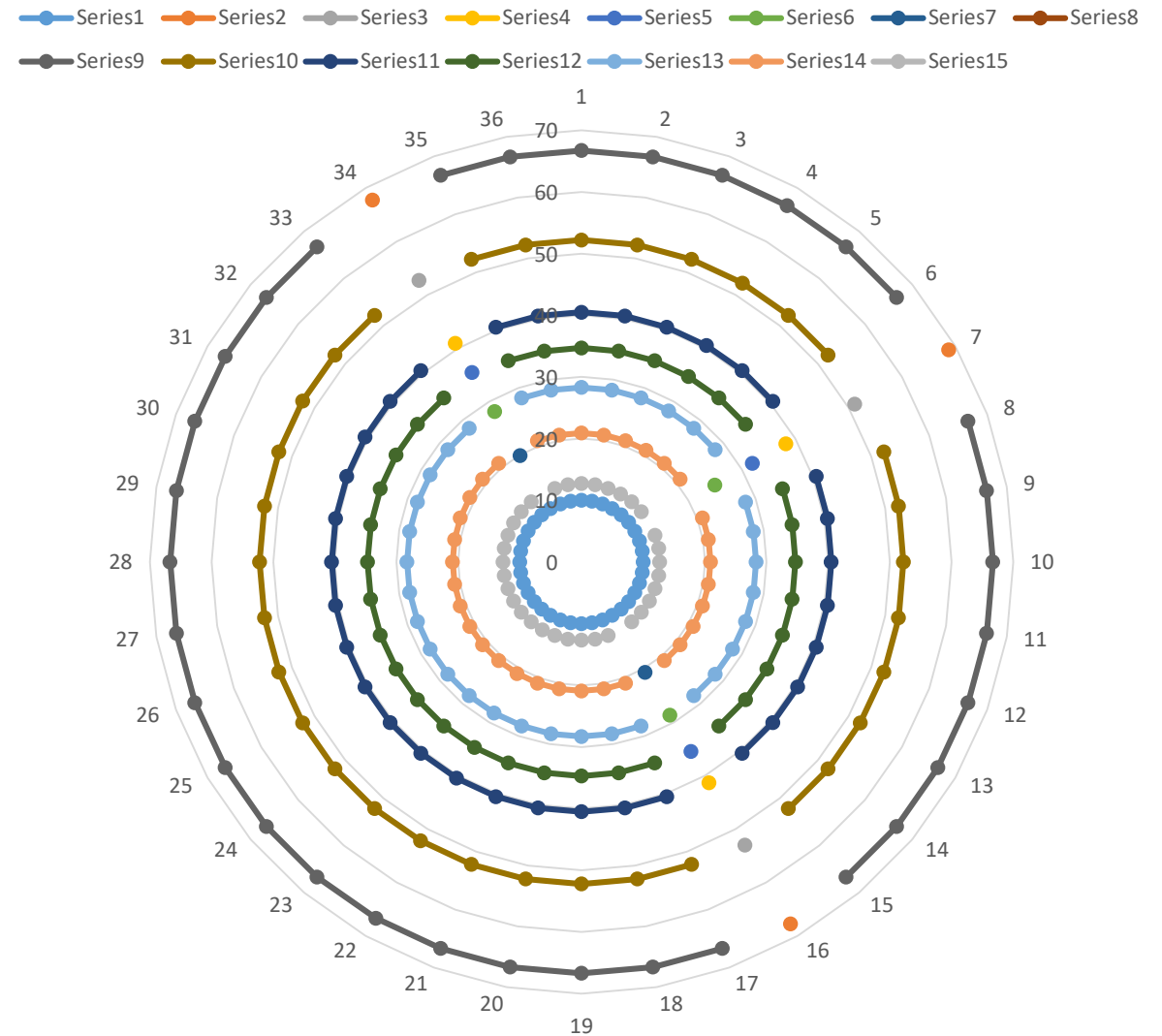
+10° probes

- Initial inner radius of liner is 75 mm.
- As shown above, liner radius at signal loss
 - CMU 3; $75 - 51.24 = 23.76$ mm @ $90.56 \mu\text{s}$
 - CMU 6; $75 - 61.42 = 13.58$ mm @ $92.16 \mu\text{s}$
 - CMU 12; $75 - 62.08 = 12.92$ mm @ $92.14 \mu\text{s}$
- There were questions about relative timing of the signals on these three probes, which at the late date of the analysis were difficult to resolve, and we have not adjusted times beyond the original analysis. Since the feeling is that loss of signal on these probes was more likely due to the arrival of the glide plane interaction which was very sensitive to probe position, we have not performed the centering analysis done for the other probes above.

+ 10° CMU probes (probe angled toward the FCG) synchronized with Roxane at peak current.
Displacement corrected by $\cos 10^\circ$

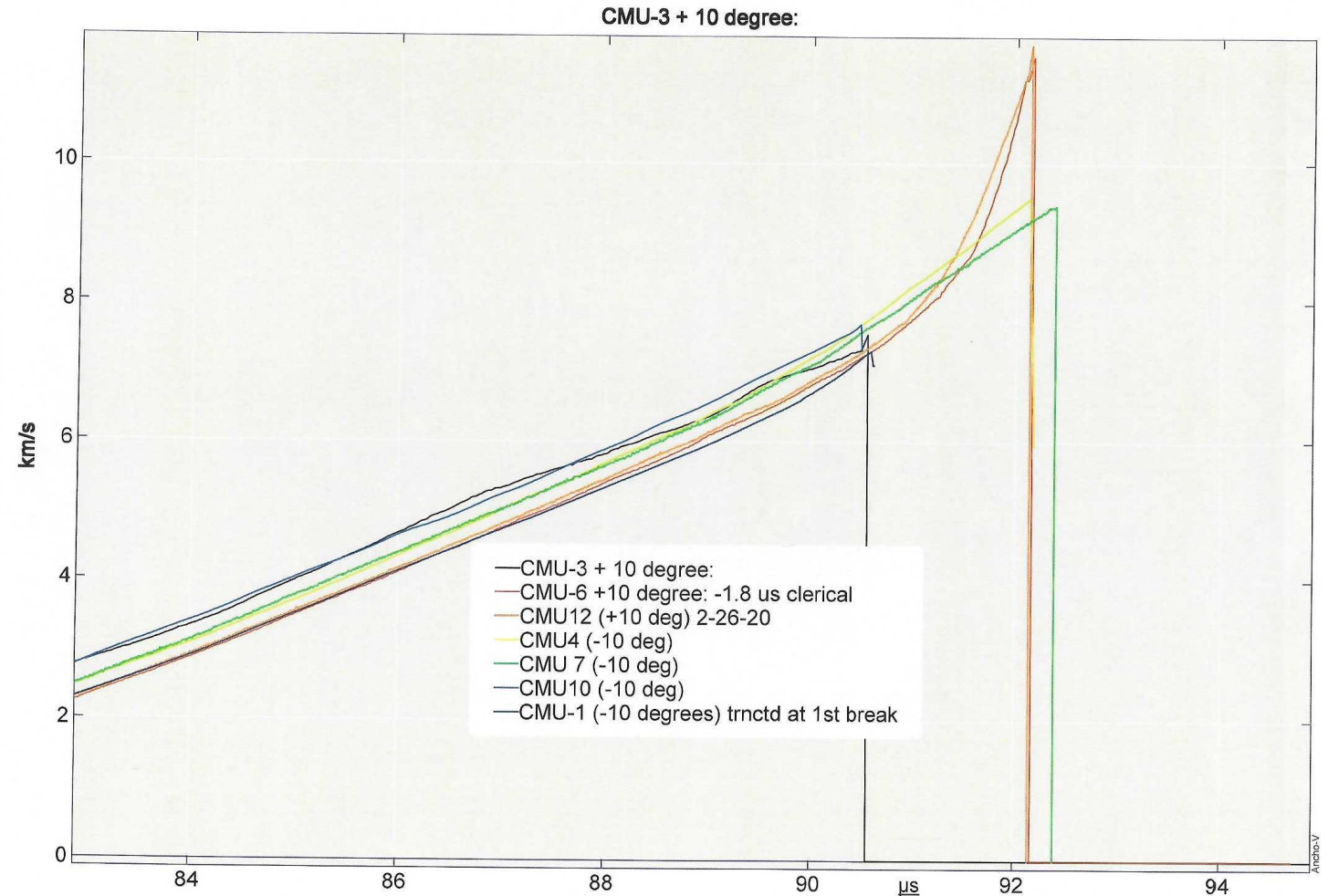
- Probes 3, 6, 12 are in positions 7, 16, and 34 respectively.
- Series 1 locates the wall of the CMU
- Compare series:
 - 2,9 [79.86 μs]
 - 3,10 [86.09 μs]
 - 4,11 [88.49 μs]
 - 5,12 [89.48 μs]
 - 6,13 [90.49 μs]
 - 7,14 [91.53 μs]
 - 8,15 [92.52 μs]
- CMU 6 and 12 [positions 16 and 34] follow the calculation almost perfectly, but CMU 3 is qualitatively different. Probe 9 failed to return data, and so one can only speculate based on these data as to the cause of the difference in probe 3. It will be shown below that small shifts in line of sight or probe position are critical, and may explain these differences.

Series 1 CMU wall, Series 2-15 [PDV,Roxane]; [2,9]-79.86, [3,10]-86.09, [4,11]-88.49, [5,12]-89.49, [6,13]-90.49, [7,14]-91.53, [8,15]-92.52



All angled probes plotted together. The angled probes have different features

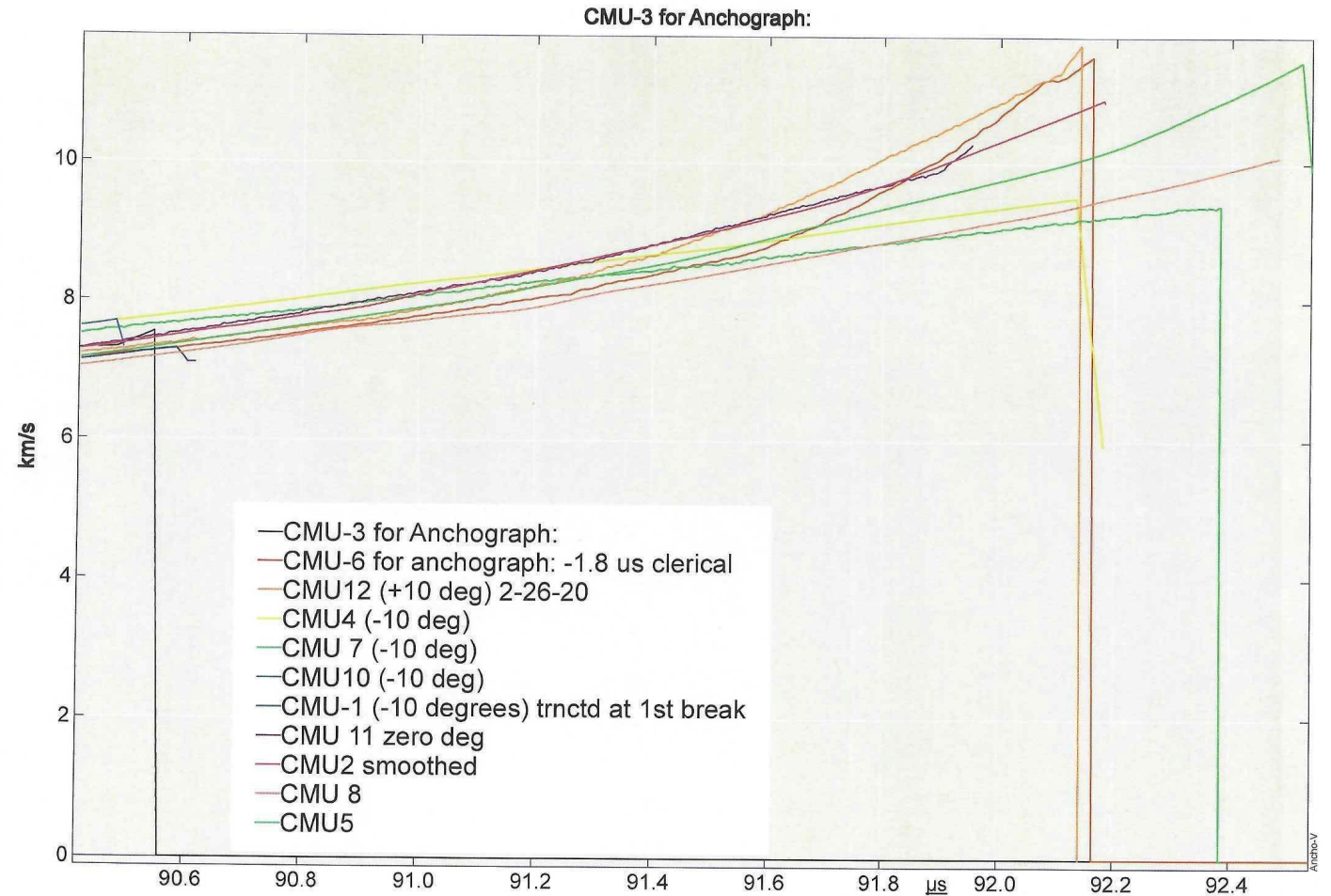
- At $\sim 90.5 \mu\text{s}$, probes 3 (+ 10°) and 1 and 10 (- 10°) abruptly end.
- Probes, 4, 6, 7, and 12 followed the liner substantially further than the other probes. [4, 6, and 7 correlate with the center offset (page 78), but 12 does not. There were questions about timing on probe 12 which, at the late date of this analysis we did not track down.
- By about $91 \mu\text{s}$, probes 6 and 12 show an increased acceleration not present on probes 4 and 7, which also continued to give a signal at these later times.
- The sudden acceleration can be interpreted as the arrival of the "glide plane foot" (see upcoming calculational frames) and was seen only + degree probes.
- Probes 4 and 7 see no strong acceleration even though they followed the liner for the same length of time.
- The straightforward interpretation is that the liner performs completely differently along the two different glide planes.
- An alternate interpretation is a mis-alignment of the angled probes or mis-positioning of the CMU. Pages 85-87 below show that a shift along z could easily be the source of this difference.
- The following slide adds 0° probes 2, 5, 8, and 11 to the plot for further evaluation.



6821B723AB6449cf973968F148E8301D.all angled prbs vel rox time.awf 01/27/21 03:01 PM

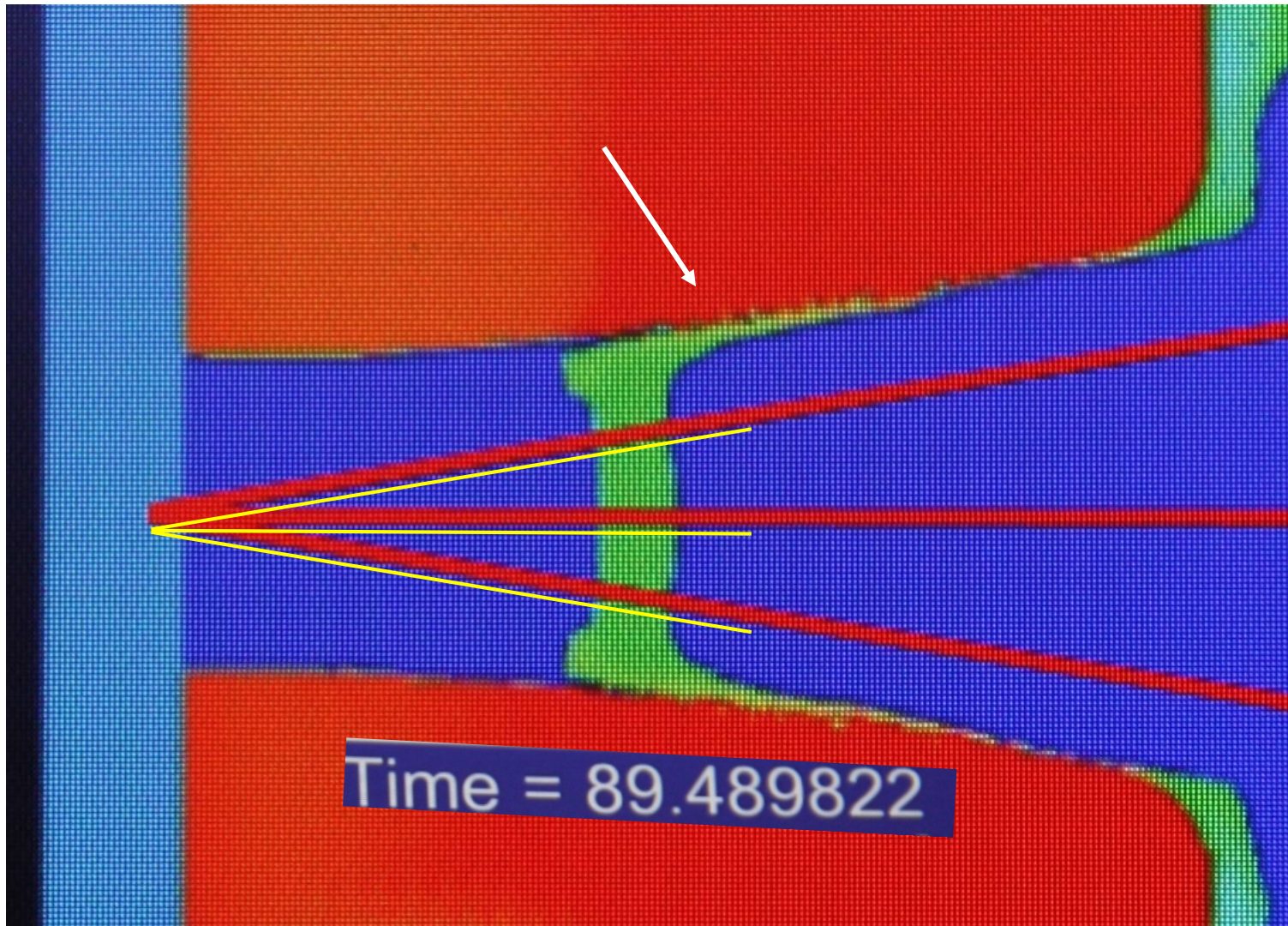
Late time acceleration is most evident on two + 10° probes

- + 10° probes have a strong acceleration starting before 91.5 μ s.
- The 0° probes show increasing acceleration late in time, but not with the abrupt start seen on the + 10° probes.
- - 10° probes either have a constant acceleration or are cut off at late times.
- The straightforward analysis would say that the performance of the liner was completely different along the +angle glide plane, and that interpretation can not be dismissed.
- However, pages 87-89 show a plausible explanation based on slight probe misalignment.



All probes Rox time frame.awf 02/01/21 03:02 PM

The yellow rays represent an $\sim 1\text{mm}$ displacement in the z direction of probe centers, and show that the angled probes could begin to see the glide-plane interactions almost $3\ \mu\text{s}$ before CMU impact given that much mis-positioning.



yldstr0

4.000e-03

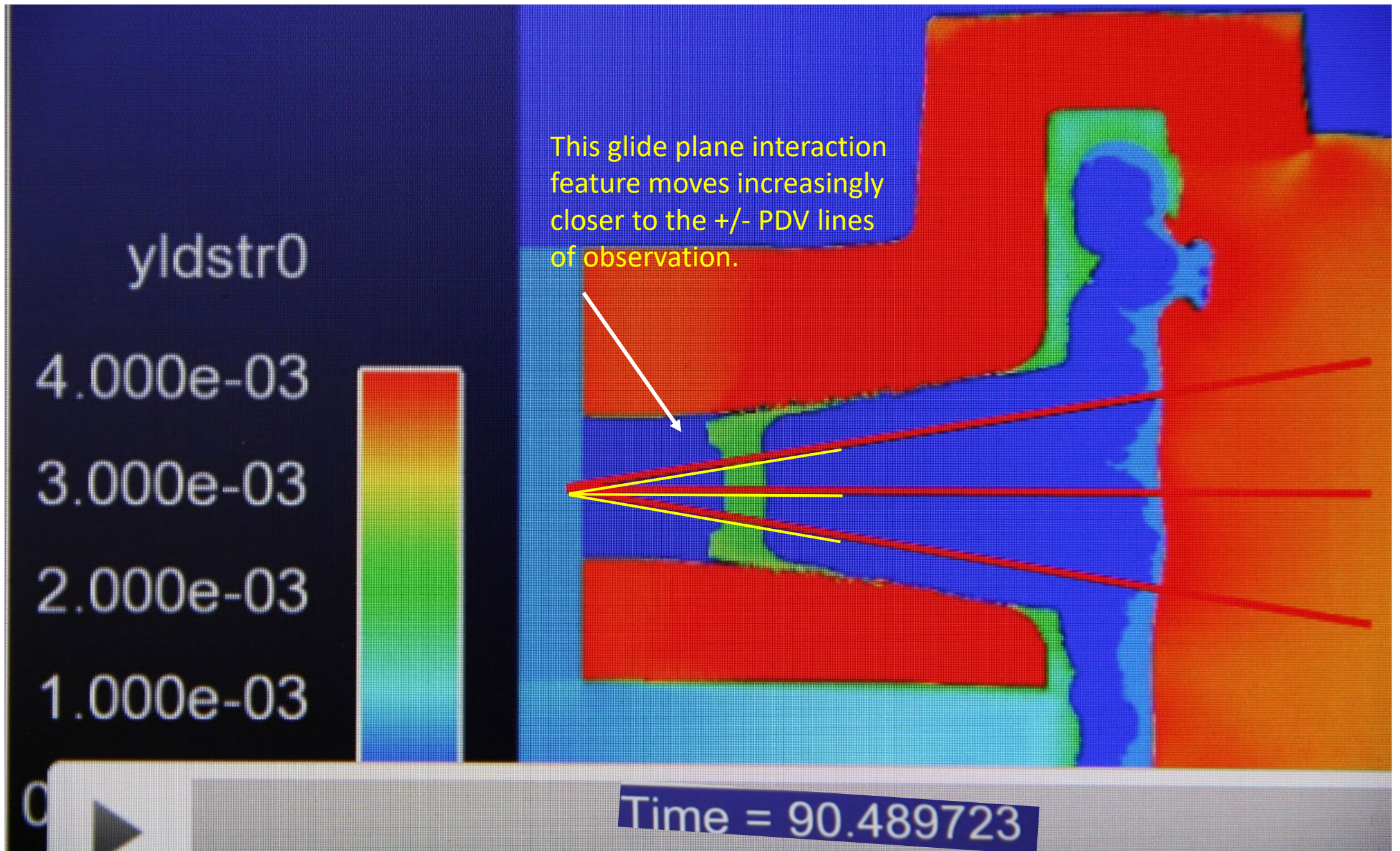
3.000e-03

2.000e-03

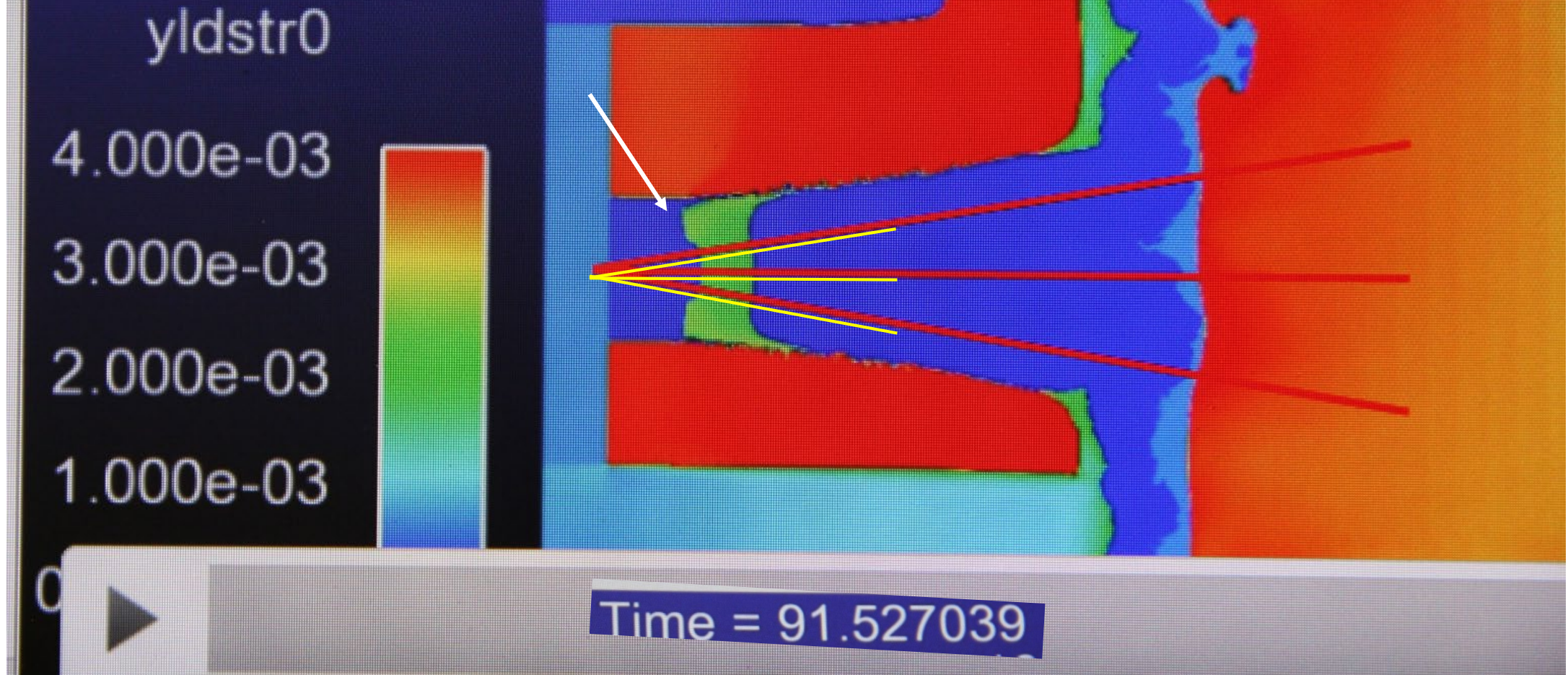
1.000e-03

This glide plane interaction
feature moves increasingly
closer to the +/- PDV lines
of observation.

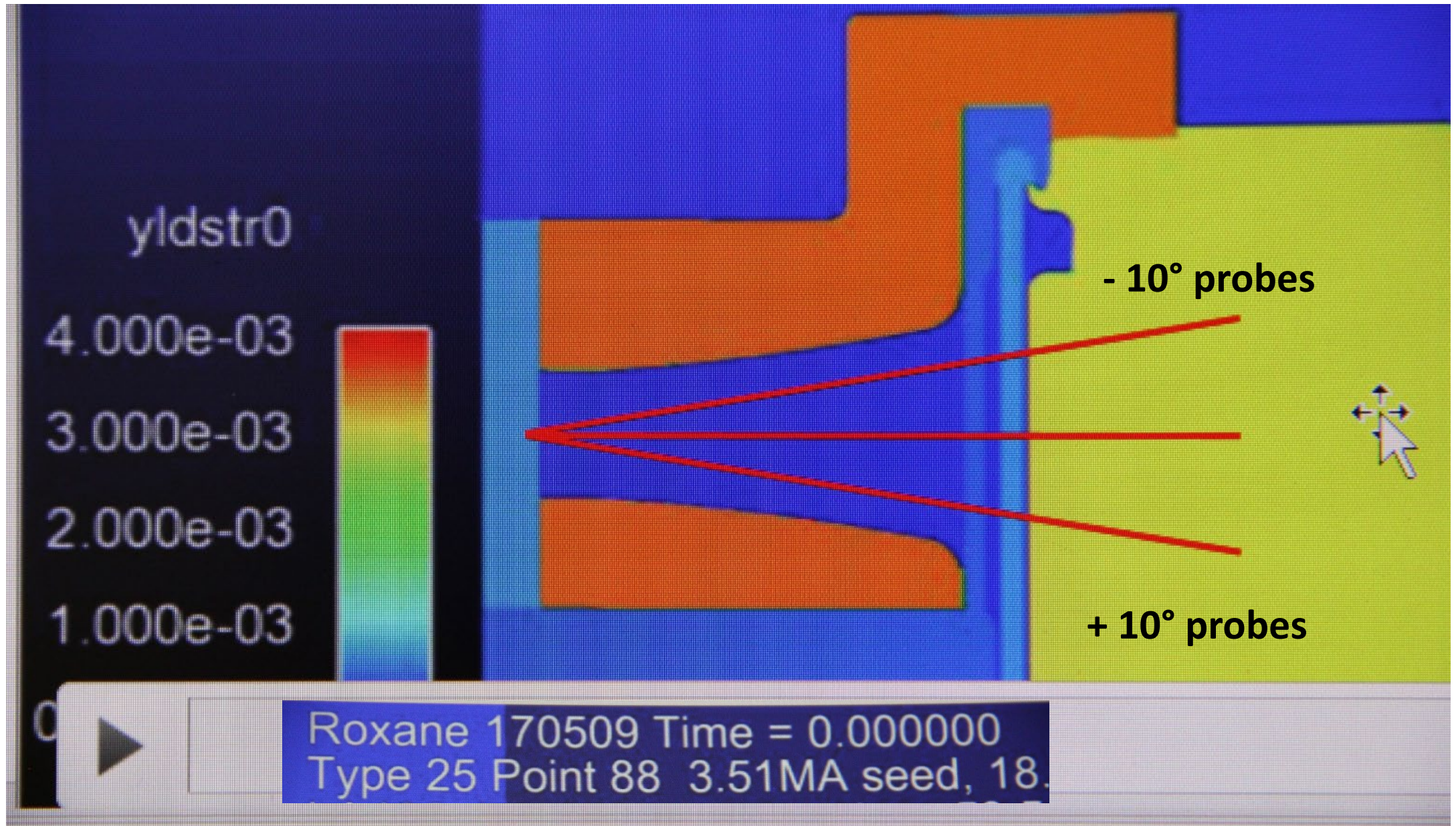
Time = 90.489723

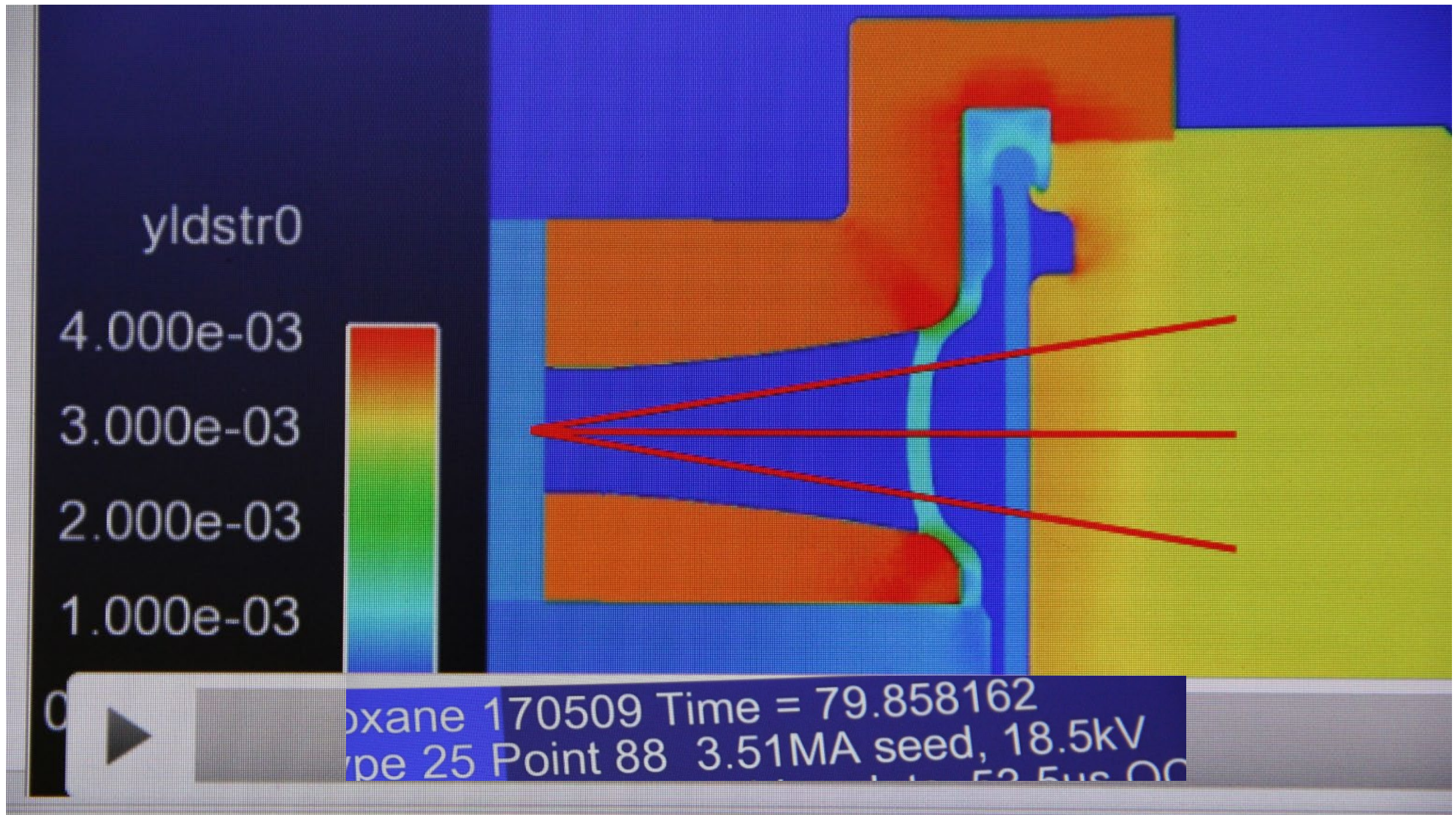


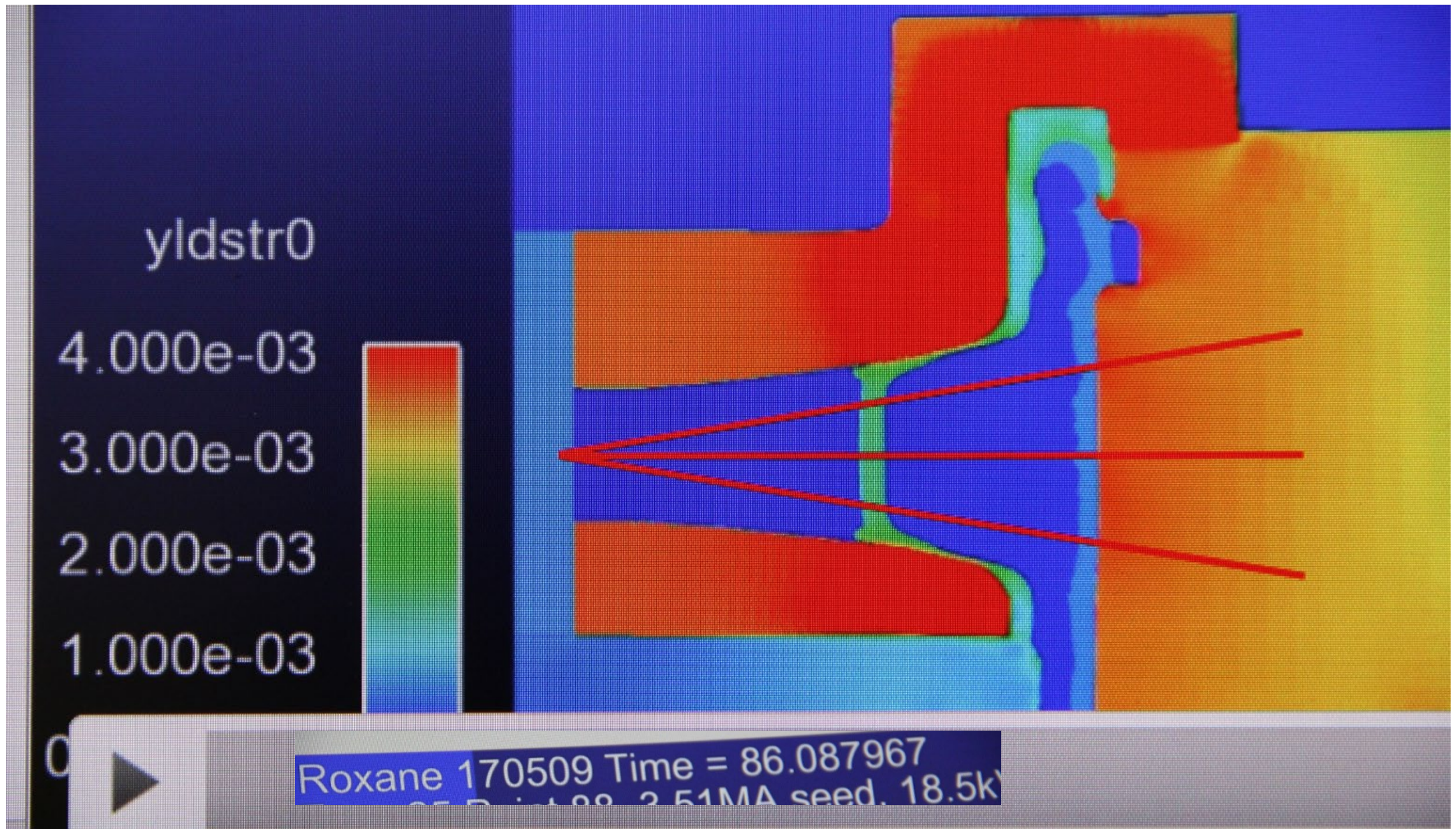
Two of the -10° probes are still giving a signal past this time but show no “glide plane interaction” foot. Two of the $+10^\circ$ probes show a dramatic acceleration about this time and the other has lost signal.

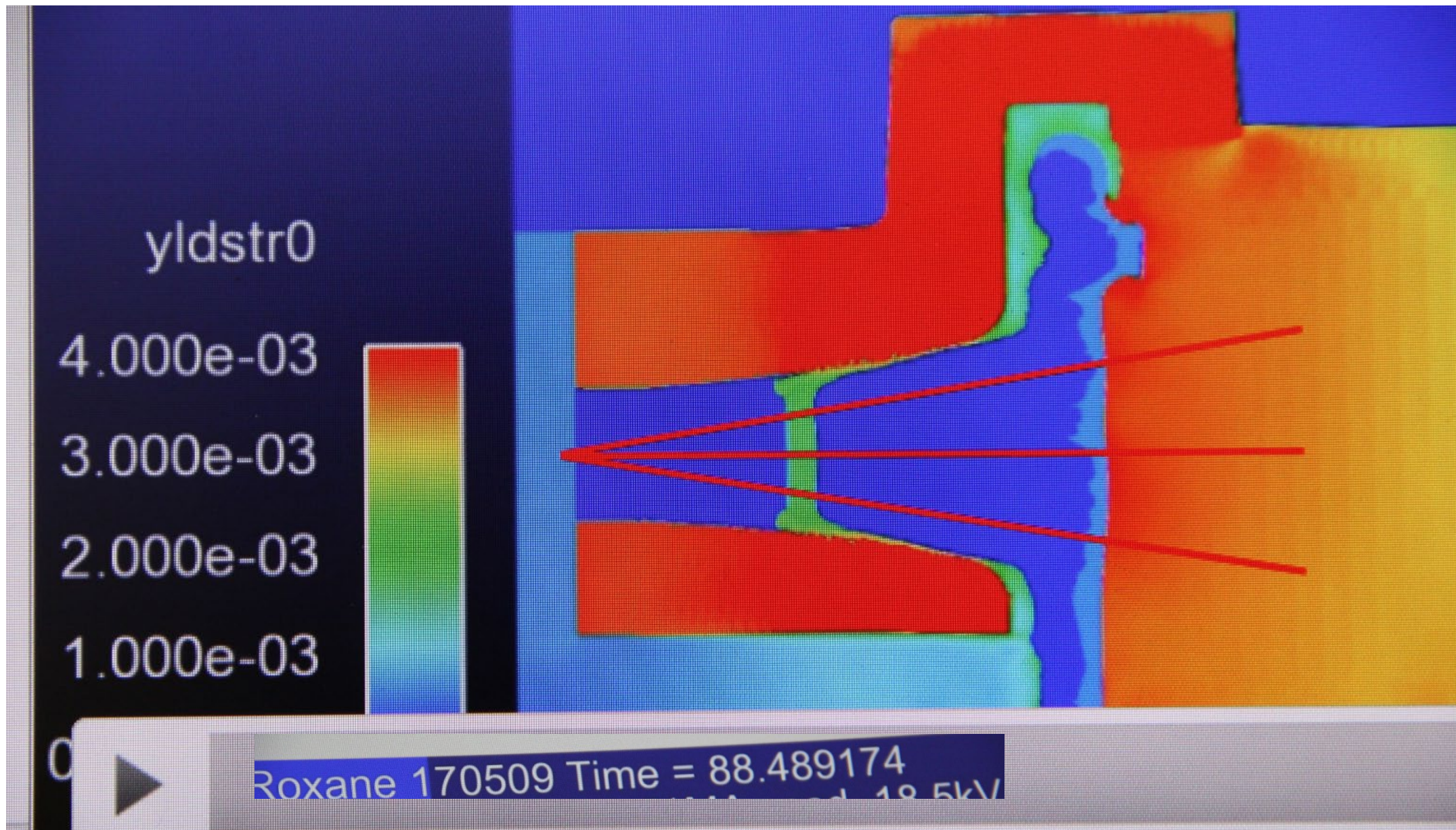


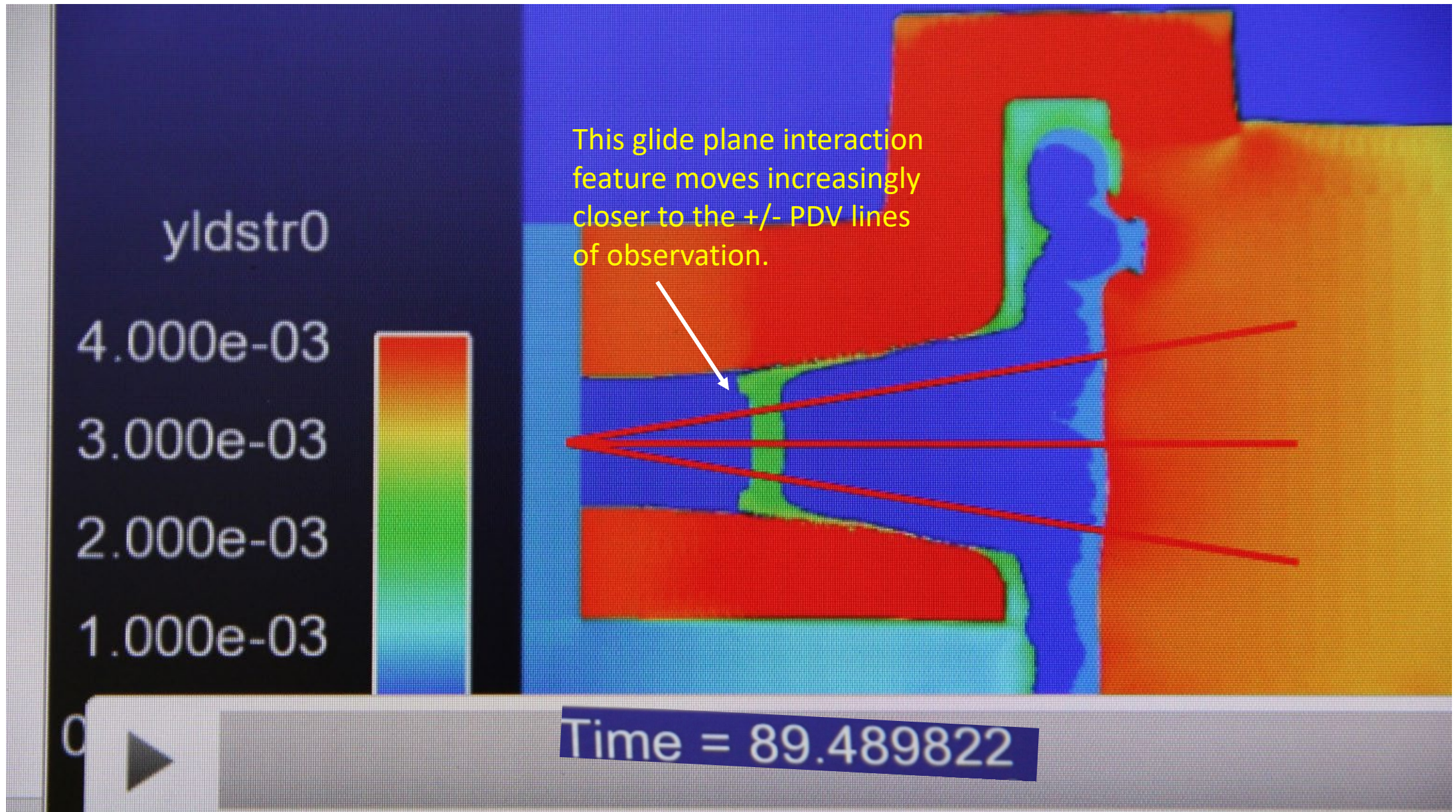
The following figures show the Roxane frames used in the above analysis with the approximate lines of sight for the PDV probes superimposed on them.











yldstr0

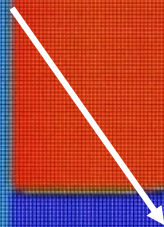
4.000e-03

3.000e-03

2.000e-03

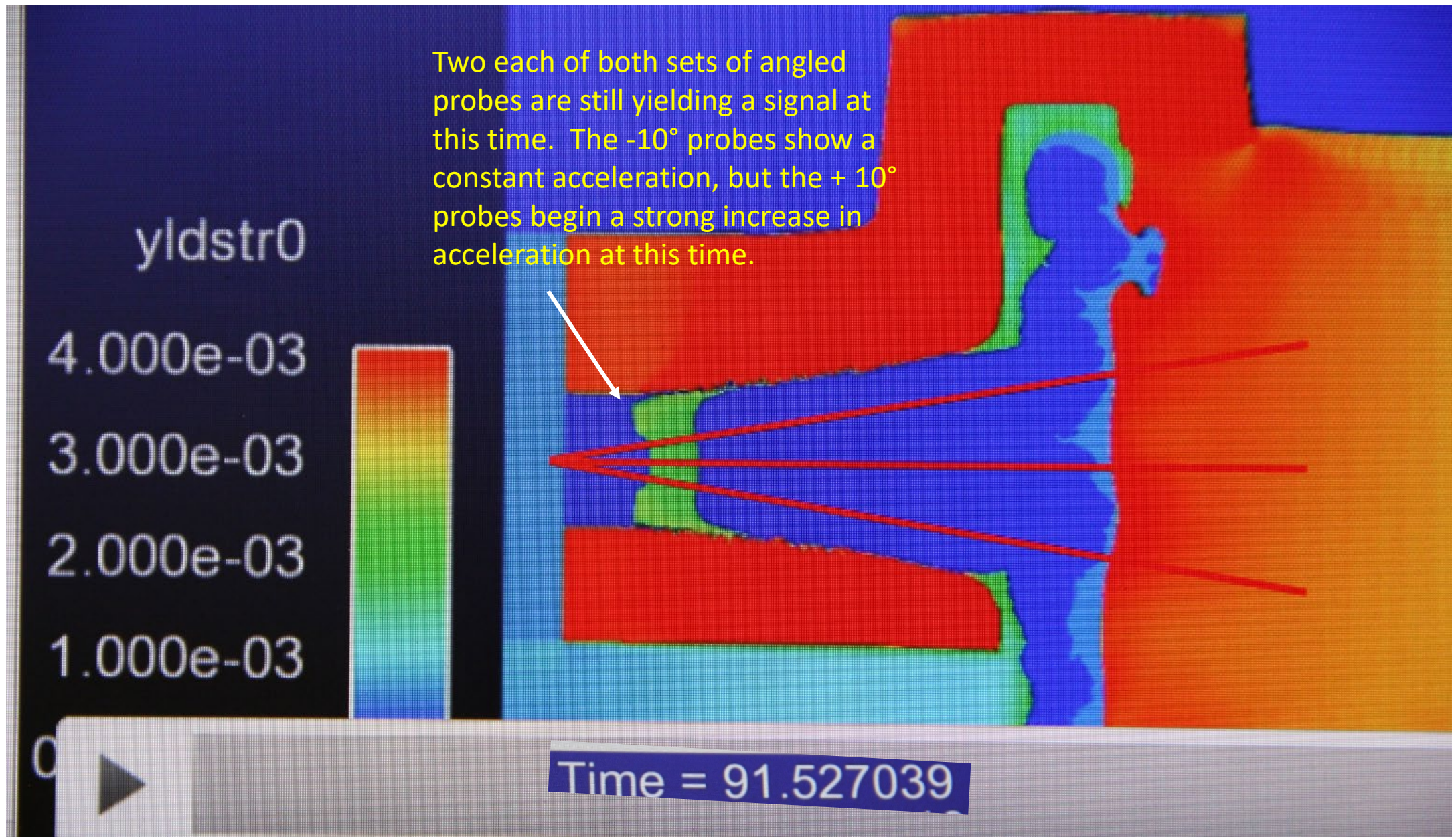
1.000e-03

This glide plane interaction
feature moves increasingly
closer to the +/- PDV lines
of observation.



Time = 90.489723

Two each of both sets of angled probes are still yielding a signal at this time. The -10° probes show a constant acceleration, but the $+10^\circ$ probes begin a strong increase in acceleration at this time.



None of the angled probes are still giving a signal at this position. However probe 7 (-10° on the late side) does last until 100 ns before this, and 0° probes 5 and 8 (also late side) last until this time.

yldstr0

4.000e-03

3.000e-03

2.000e-03

1.000e-03

0

Time = 92.526634

Conclusions

- The Ranchero R43S6 FCG - below
- CMU PDV analysis - below
- All systems functioned as expected, but more engineering is required for future models of the pneumatically powered slapper firing unit in order to reduce the volume required.
- Better calibrations are very important for current diagnostics.

Conclusions – Ranchero R43S6 - FCG

The Ranchero R43S6 FCG gave a nominal performance. Pre-shot calculations with the Roxane code [Appendix IV] predicted more current at peak than achieved (~ 42 vs ~ 36.35 MA), but in the time between those calculations and post shot evaluation, it was discovered that Roxane's magnetic field diffusion solver was inadequate. Roxane calculations performed shortly after the experiment (Bob Watt 170509) with the updated diffusion solver gave excellent agreement with current multiplication. On the test, the FCG achieved a gain of $36.4 \text{ MA} / 3.5 \text{ MA} = 10.4$ with a load that was initially 2.5 nH , but grew to 3.9 nH by peak current, using CMU PDV data to determine liner position. At CMU impact, one estimates from MHD calculations that the circuit inductance has increased to $\sim 8.5 \text{ nH}$ and the current in calculation is 19.5 MA . The output Rogowski coils on the 43-S did not survive to final implosion time. The "waste inductance" of the swooped FCG with an anodized stator is essentially the same as earlier Ranchero FCGs that were insulated with wraps of polyethylene, and these wraps will not be used in the future. The time delay from armature first motion to actual crowbar was longer than on previous experiments and this was traced to a larger gap than previous between the armature and stator. Analysis shows that this reduced the peak current by less than 1 MA , and future tests will not revert to the smaller gap in order to facilitate easier assembly.

To generate higher current with the same or larger inductance loads, larger initial currents will be required. By the time this report has been prepared, a new booster generator, the MK-X helical FCG, has demonstrated the ability to provide up to 9 MA to an R43S6 FCG.

Conclusions – CMU PDV

The PDV data from the mid-plane [zero degree probes] show an implosion that reaches over 1.1 cm/ μ s and is about 2 mm off-center as described above on pages 79 and 80. The liner implodes slightly faster than shown in the calculation 170509, which has small timing differences from the experiment, but is a very close match. The initial current pulse in the experiment is shorter by 1.5 μ s than in the calculation, but the R43S6 Ranchero reaches peak current more slowly by 1.6 μ s than in the calculation. The two differences compensate to produce a very similar profile.

Analysis of the angled probes leaves a question that can not be answered with complete confidence. The straightforward interpretation is that the liner performance is completely different along the opposite glide planes. This can't be dismissed, but the validity of the calculations is confirmed for the rest of the test so thoroughly that one looks for alternate interpretations. An alternate interpretation suggests that the axial position of the probes was likely shifted by some amount. There are two +10° probes that show acceleration at late times consistent with the arrival of the glide plane interaction predicted by the calculations. There are two -10° probes that follow the implosion for the same length of time, but never show the greatly increased acceleration profile. The zero degree probes fall in between the two sets of angled probes, and the conclusion is that the line of sight of the -10° probes never saw the glide plane effect and the +10° probes saw the glide plane interaction earlier than expected. Not all of the angled probes produced a signal late in time, and the speculation is that in those cases glide plane effects caused the PDV return signal to be lost.

The analysis of the angled probes required extra steps, and future shots should re-consider the difference between viewing the implosion from a single axial position with angled probes to observe glide plane effects, or viewing the implosion from different axial positions and risking glide plane effects to cause the signal to be lost prematurely. In either case, this test shows that, at least for some perturbed surfaces, a return signal can be seen. Further, great care must be taken in the future to assure probe alignment. For this first of its kind test, the alignment fixture gave confidence that the angles were accurate within some undefined accuracy, but there was no evident control that the z positioning was guaranteed to be highly accurate.

References

1. LA-43-S-CT Post Shot, LA-UR-19-20124, Jim Goforth, Chris Armstrong, Eva Baca, Peter Dickson, Tim Foley, Jake Gunderson, Dennis Herrera, Philip Rae, Chris Rousculp, Robert Watt, Los Alamos National Laboratory and Erik Haroz, Mission Support & Test Services- Los Alamos Operations
2. Ranchero Status Report 2012, LA-14463, J. H. Goforth, M. L. Alme, W. L. Atchison, B. B. Glover, D. H. Herrera, D. B. Holtkamp, G. Idzorek, E. C. Martinez, R. K. Meyer, E. M. Nelson, D. B. Reisman, H. Oona, D. M. Oro, P. J. Rae, R. L. Reinovsky, G. Rodriguez, C. L. Rousculp, A. G. Sgro, M. G. Sheppard, L.J. Tabaka, D. G. Tasker, D. T. Torres, and R. G. Watt
3. Predictions for the drive capabilities of the RancheroS Flux Compression Generator into various load inductances using the Eulerian AMR Code Roxane, R. G. Watt, LA-UR-16-23924, 5/29/2016
4. The search for a 100 MA RancheroS magnetic flux compression generator, LA-UR-16-26685, R. G. Watt, 8/29/16.
5. Ranchero Armature Test LA-19.4-CT-3: PBX-9501 Explosive with no smoothing layer, Firing point 88, 9/16/13, Brian Glover, Jim Goforth, Philip Rae, Peter Dickson, Matt Briggs, Mark Marr-Lyon, Steve Hare, Dennis Herrera, Bob Watt, and Chris Rousculp, LA-UR-14-28810
6. The Quest For The Wholly Stable Liner, W. L. Atchison et al., "Proceedings of the 2006 International Conference on Megagauss Magnetic Field Generation and Related Topics, Nov. 2006, Santa Fe, NM, Kiuttu, Reinovsky, Turchi, eds. pp 57.

Appendices – Title pages for the Appendices are given below, and the complete documents are stored on an M-6 shared drive along with the Power Point version of this report. See M-6 personnel

Appendix I:

Small scale tests '15

Post Shot draft

11/17/15

Currently an amalgamation of Rousculp and Goforth

Appendix II

LA43S liner implosions, Roxane results: for
discussion and Goforth's IEEE2015 talk

R. G. Watt

150511

Appendix III

Comparison of LA43S_L1 data and Roxane Postshot Simulations

R. G. Watt 170525

Appendix IV

Preshot predictions for LA-43S-1 using the
Eulerian AMR code Roxane

R. G. Watt 11/18/2015